# Recent progress of understanding 3D magnetic topology in stellarators and tokamaks

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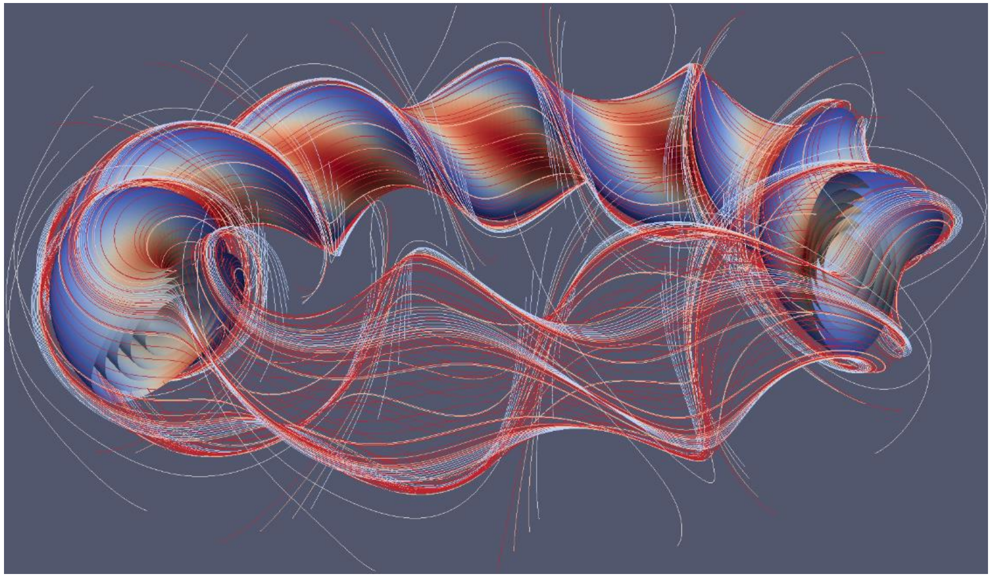
2. HINT: a 3D MHD equilibrium calculation code
3. Impacts of beta-sequences to magnetic topology in stellarators and tokamaks
4. Impacts of toroidal rotation on magnetic islands
5. Summary and outlook

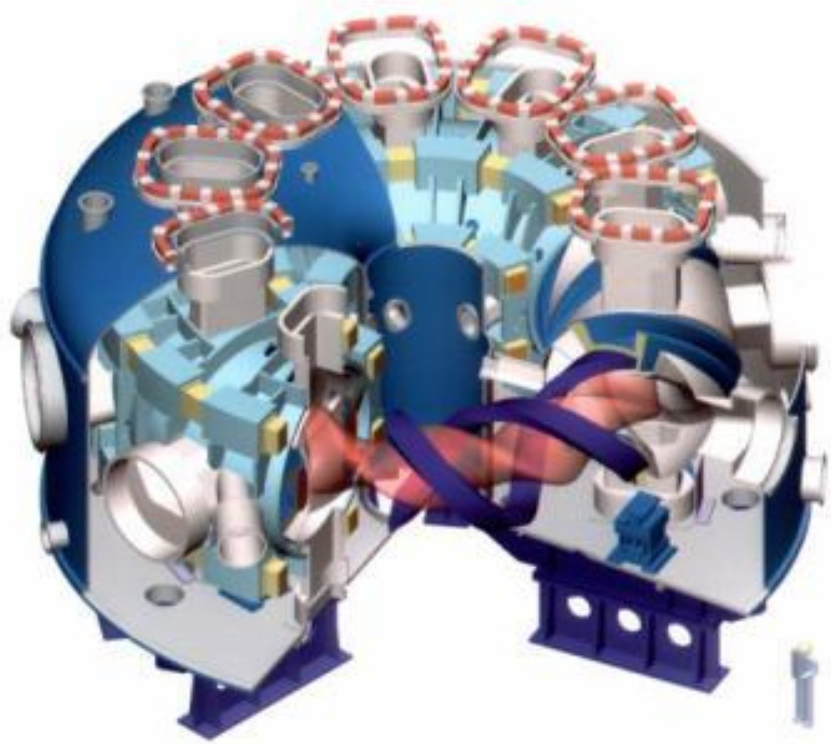
# Background

- LHD is an L/M=2/10 Heliotron configuration. The stochastization of magnetic field lines naturally appears because of no symmetry.

**Flux surfaces**



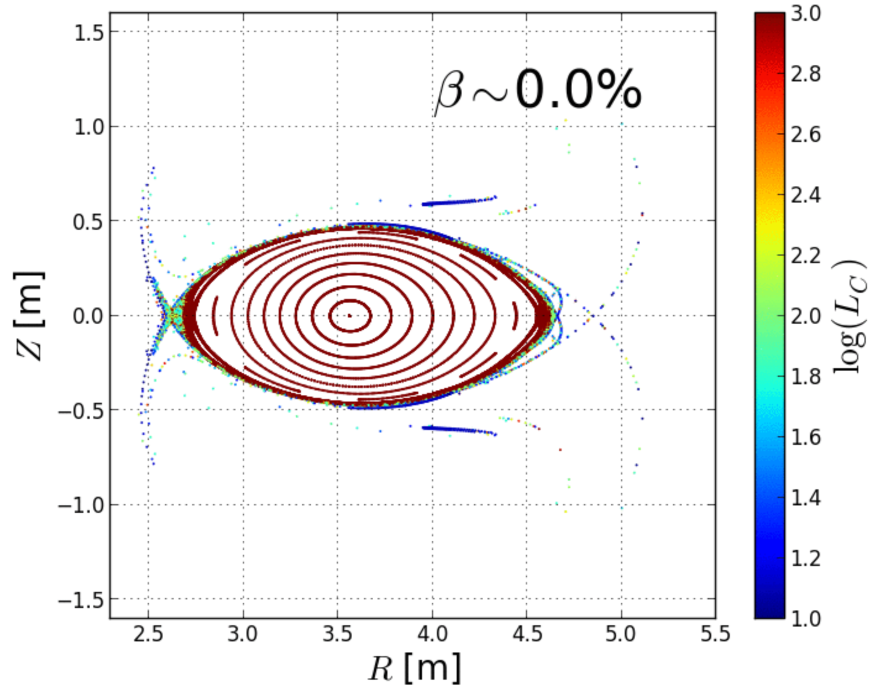
**Large Helical Device**



# Background

- LHD is an L/M=2/10 Heliotron configuration. The stochastization of magnetic field lines naturally appears because of no symmetry.
- In addition, 3D MHD equilibrium analyses predict the stochastization by the "***nonlinear 3D equilibrium response***". That is, magnetic field lines are further stochastized by pressure-induced perturbed field driven by currents along rippled field lines.

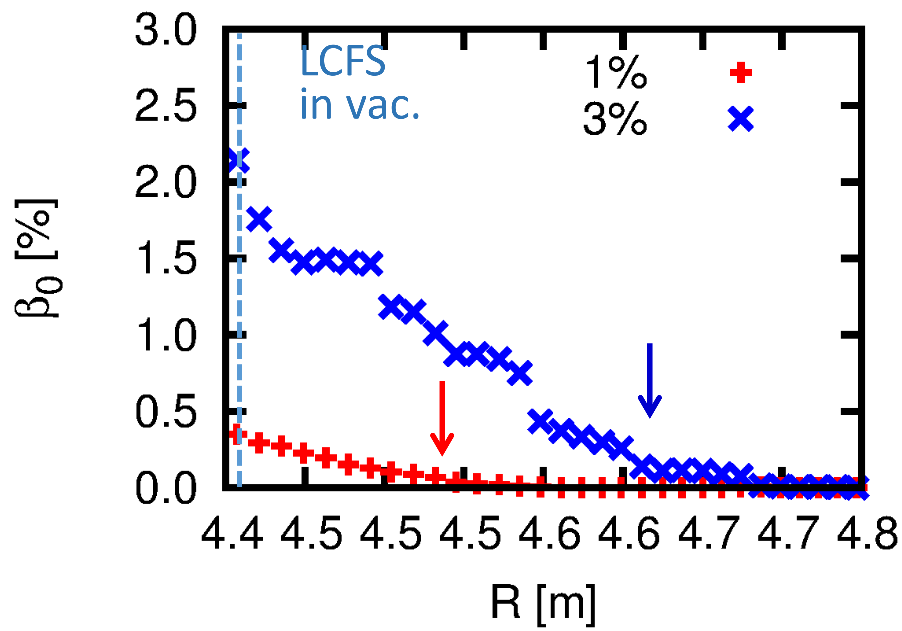
**3D MHD modeling by HINT**



# Background

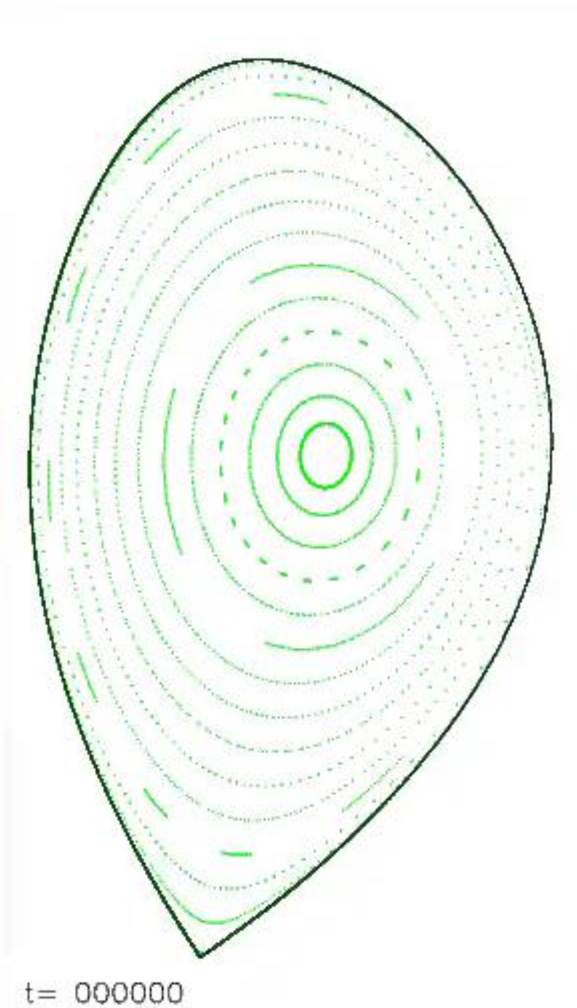
- LHD is an L/M=2/10 Heliotron configuration. The stochastization of magnetic field lines naturally appears because of no symmetry.
- In addition, 3D MHD equilibrium analyses predict the stochastization by the "***nonlinear 3D equilibrium response***". That is, magnetic field lines are further stochastized by pressure-induced perturbed field driven by currents along rippled field lines.
- In experiments, changing the boundary of plasma pressure is observed. Increasing β, the boundary shifts to the outward of the torus.

**Pressure profiles with different β**




**Magnetic topology changed!**

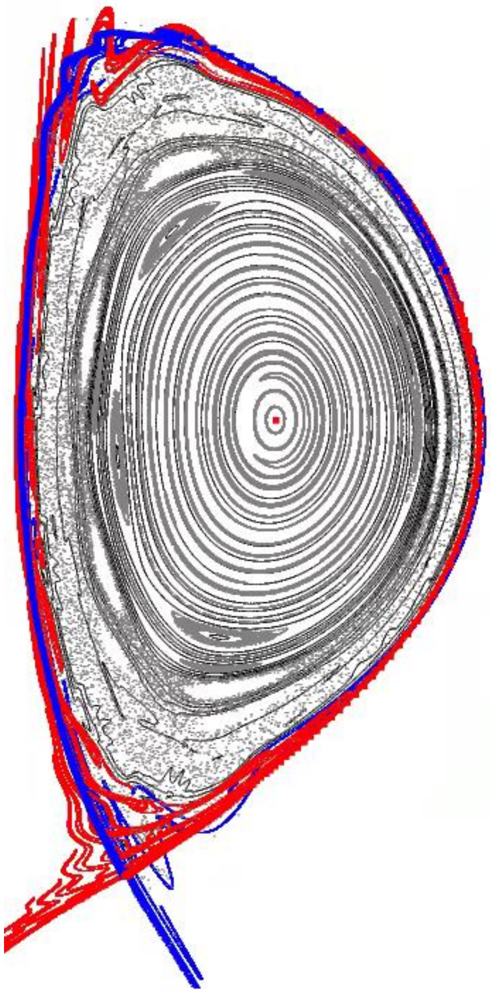
# 2D boundary in axisymmetric torus




**In axisymmetric torus (2D system), plasma boundary can be defined clearly on separatrix or limiter.**

**2D plasma boundary separates nested flux surface region and scrape-off layer (SOL), open field line region.**

# 3D stochastic boundary in non-axisymmetric system



**However,**

**In non-axisymmetric torus (general 3D system), perfectly nested flux surfaces cannot be guaranteed.**

**The magnetic field of 3D system consists of 3 regions.**

1. **Nested flux surfaces**
2. **Stochastic layer (long $L_C$)**
3. **Scrape-Off layer (short $L_C$)**

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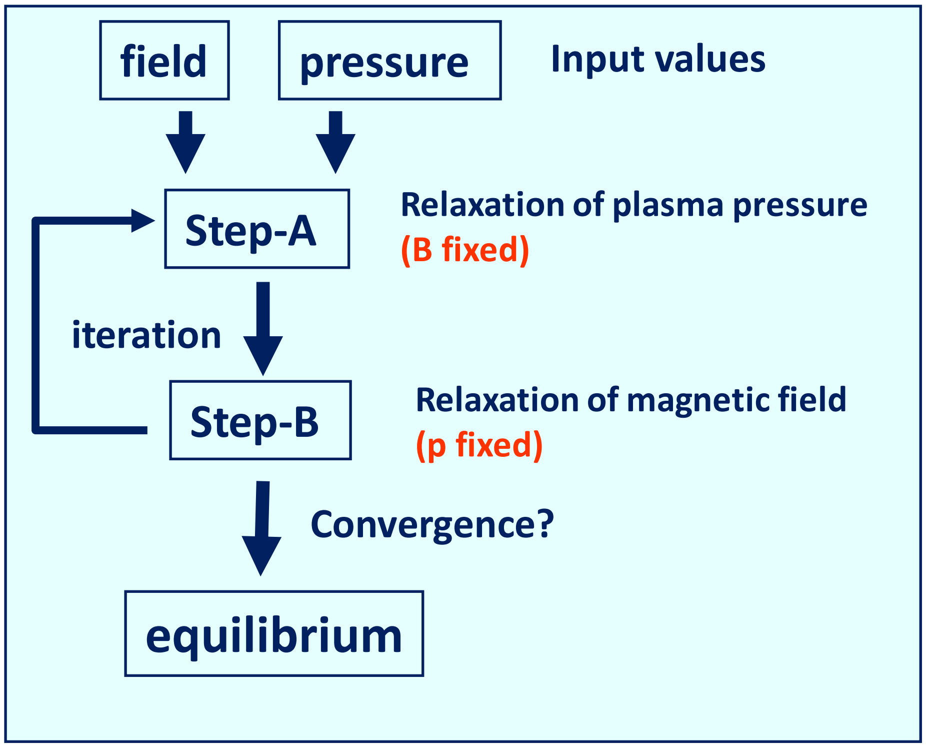
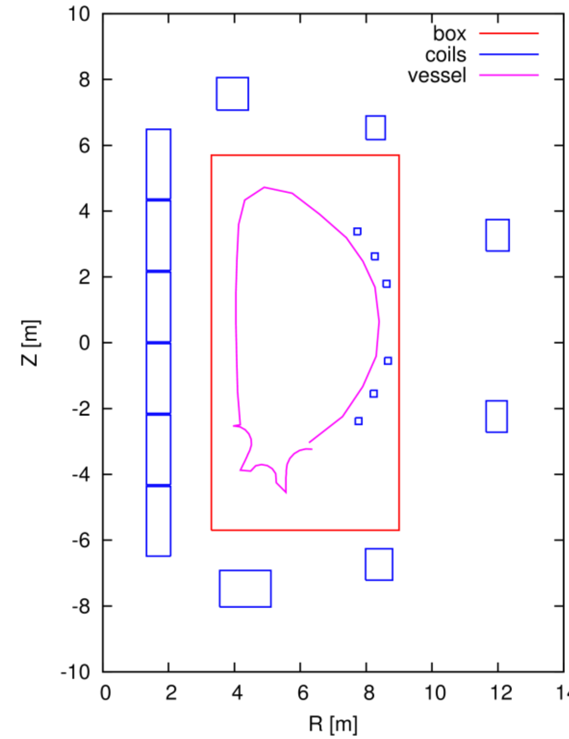
# HINT : a 3D MHD equilibrium calculation code

HINT is a 3D MHD equilibrium calculation code without assumption of nested flux surfaces. ⇔ VMEC (assuming nested flux surfaces)

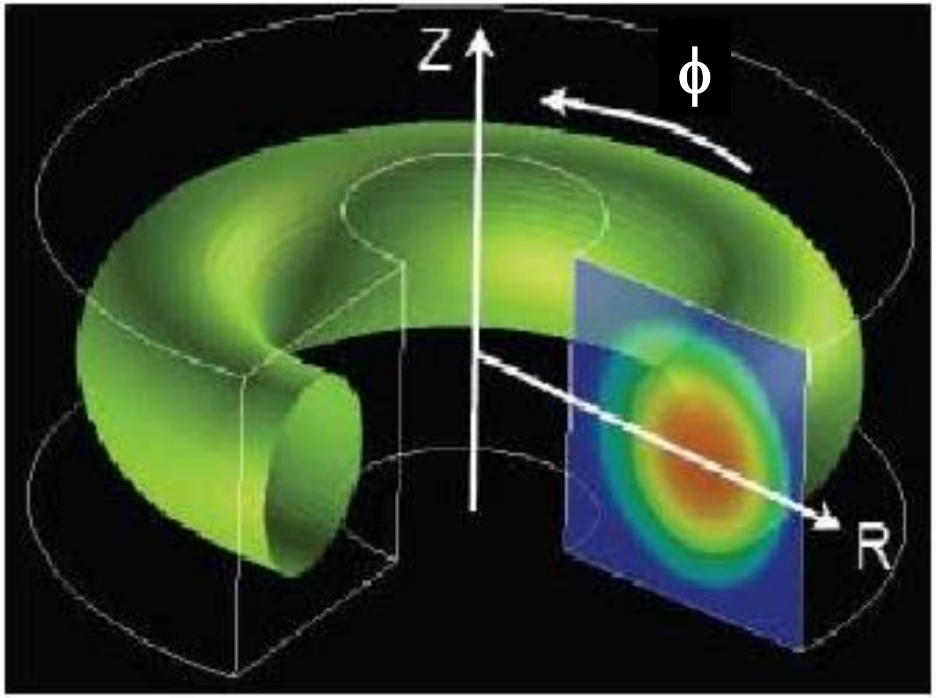
- relaxation method ( initial value problem )
- Eulerian coordinate( cylindrical coordinate ($R, \phi, Z$) )




An example



# Numerical model




[Mizuguchi 2012]

- **Rectangular Grid on the cylindrical coordinates (R,ϕ,Z)**
- **4th order finite difference**
- **4th order Runge-Kutta method for time integration**

**Our approach is the DNS ( Direct Numerical Simulation ).**

# Step-A : Relaxation of plasma pressure

**This process calculates constant pressure along field line. (B fixed)**

$$\mathbf{B} \cdot \nabla p = 0 \quad \Longleftrightarrow \quad p^{i+1} = \bar{p} = \frac{\int_{-L_{\rm in}}^{L_{\rm in}} \mathcal{F} p^i \frac{dl}{B}}{\int_{-L_{\rm in}}^{L_{\rm in}} \frac{dl}{B}}, \quad \mathcal{F} = \begin{cases} 1 & : \quad \text{for } L_C \geq L_{\rm in} \\ 0 & : \quad \text{for } L_C < L_{\rm in} \end{cases}$$

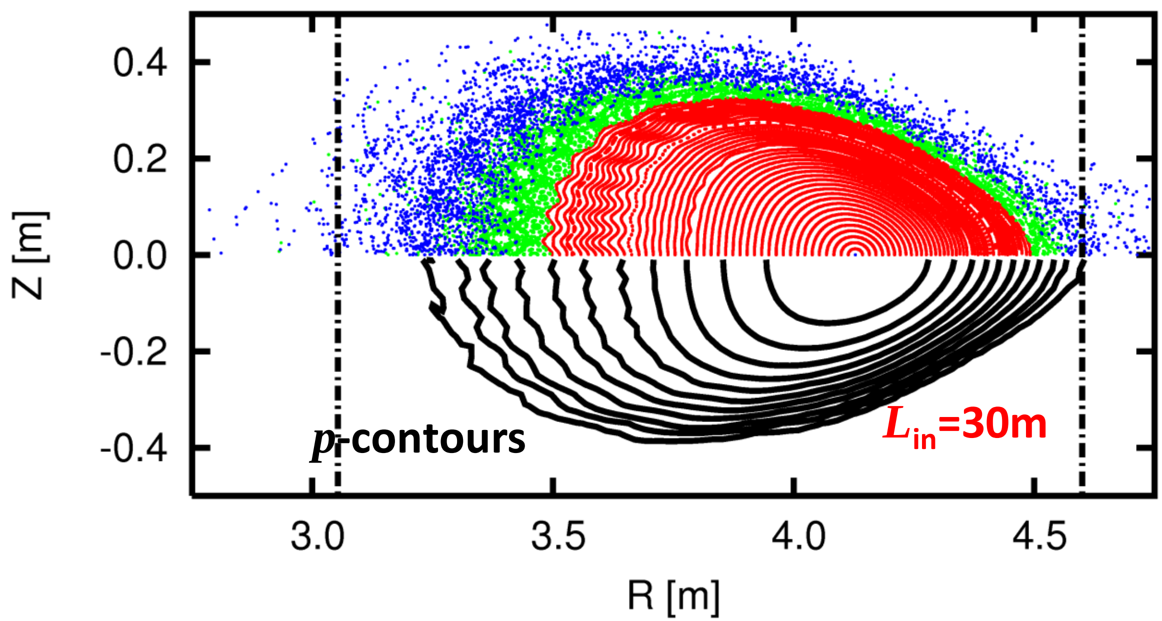
**HINT modeling**

Averaged pressure is calculated by the following equation;

If $L_C$ is longer than $\lambda_e$, stochastic field lines keep the pressure.

The structure due to the averaged pressure appears.

$R_{ax}$=3.85,$B_T$=3.0,$B_Q$=100%,$\gamma$=1.254 <$\beta$>=2.1%




From the viewpoint of the transport, the electron is sensitive within $\lambda_e$ because of perpendicular transport by Coulomb collision. Contour lines means averaged structure of field lines.

# Step-B : relaxation of magnetic field

This process calculates the time evolution of dissipative MHD equations.
(***p*** fixed)

$$
\begin{aligned}
\frac{\partial \mathbf{v}_1}{\partial t} &= -\nabla p + \mathbf{j} \times (\mathbf{B}_0 + \mathbf{B}_1) + \mu \Delta \mathbf{v}_1 \\
\frac{\partial \mathbf{B}_1}{\partial t} &= \nabla \times [\mathbf{v}_1 \times (\mathbf{B}_0 + \mathbf{B}_1) - \eta (\mathbf{j}_1 - \mathbf{j}_{\mathrm{net}})] \\
\mathbf{j}_1 &= \nabla \times \mathbf{B}_1
\end{aligned}
$$

If ***$dv_1/dt$* and *$dB_1/dt$* => 0**, calculation is convergence!

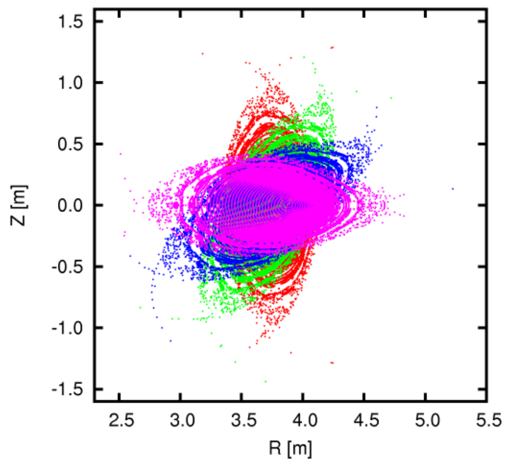
$\rho$ = 1 (constant)

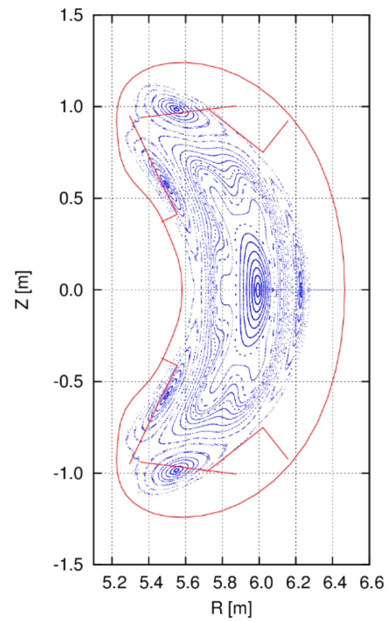
***B*** = ***B***$_0$ (vacuum) + ***B***$_1$ (equilibrium response)

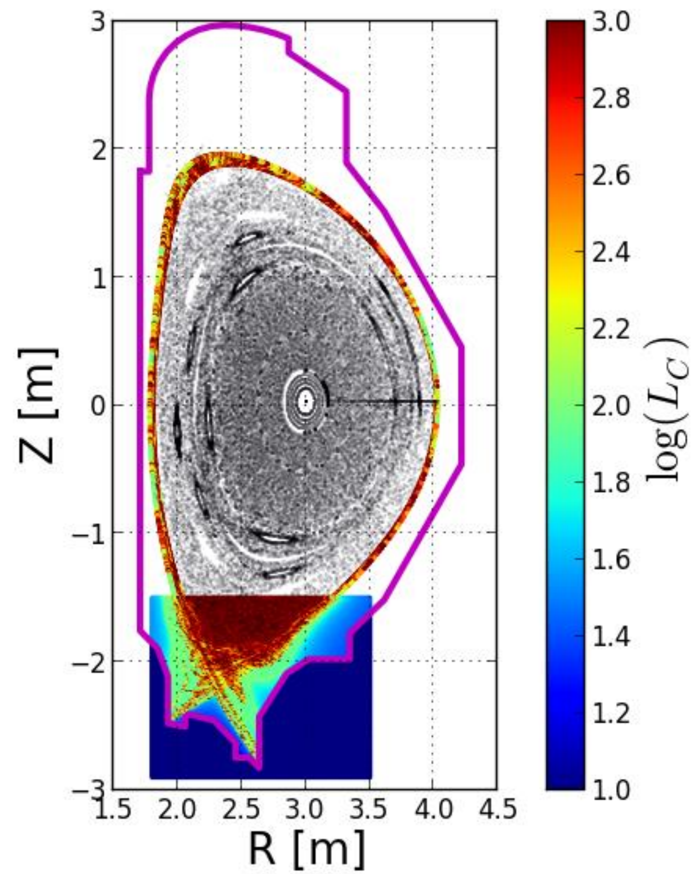
***v*** = ***v***$_1$ (MHD flow)

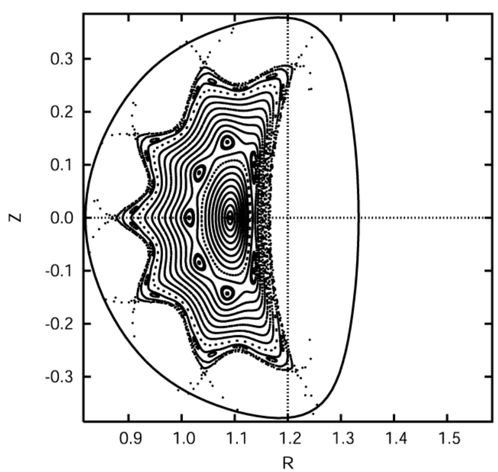
$\eta$: resistivity (constant)

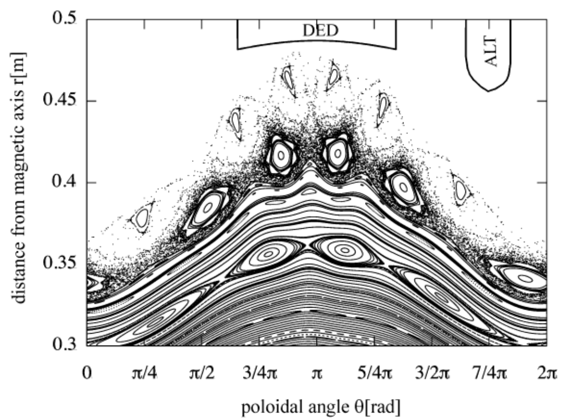
# HINT applies to many stellarator and tokamaks



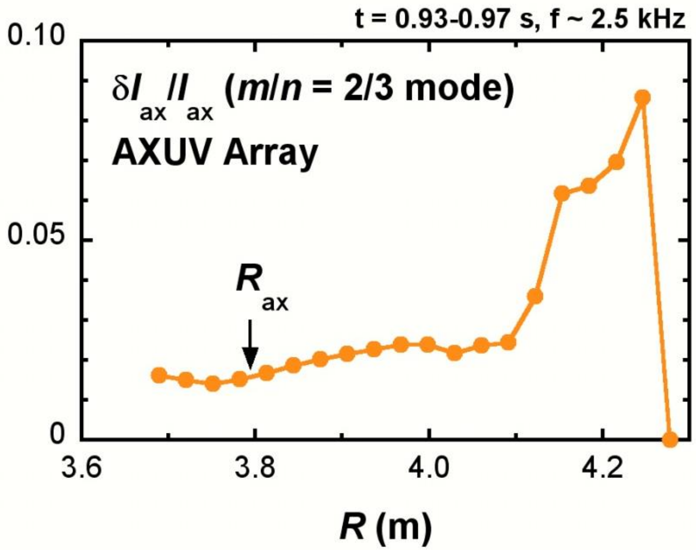

TJ-II, ITER, DIII-D, JET, MAST,…

EAST, ASDEX-U, (planning)

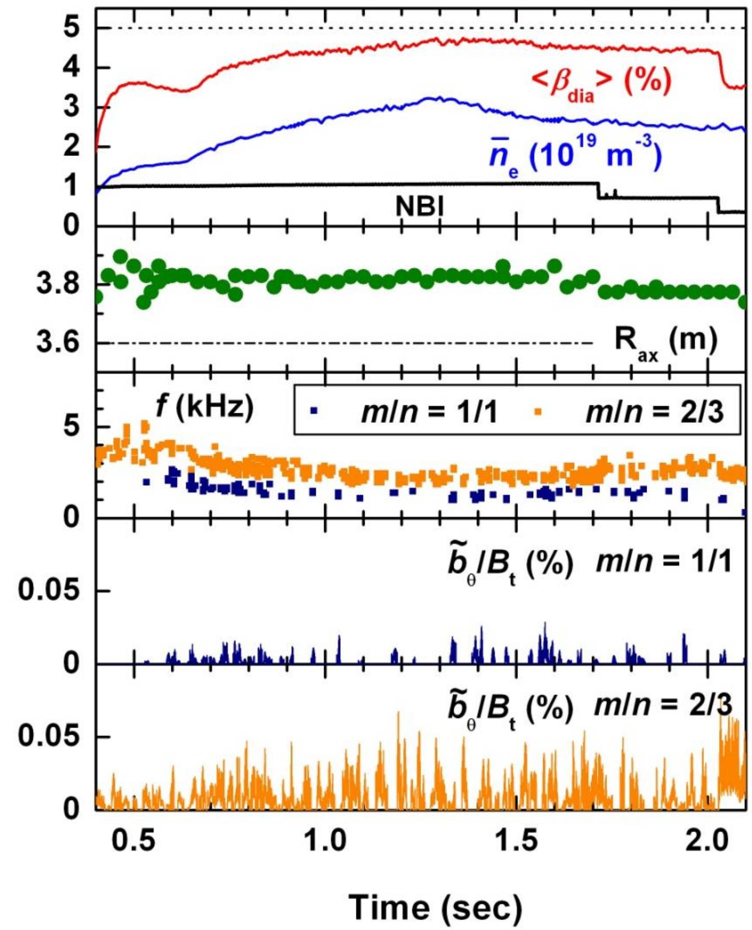
# Contents

# High-beta Steady State Discharge

- $<\beta>_{max}$ ~ 4.8 %, $\beta_0$ ~ 9.6 %, $H_{ISS95}$ ~ 1.1
- Plasma was maintained for $85\tau_E$
- Shafranov shift $\Delta/a_{eff}$ ~ 0.25
- Peripheral MHD modes are dominantly observed.

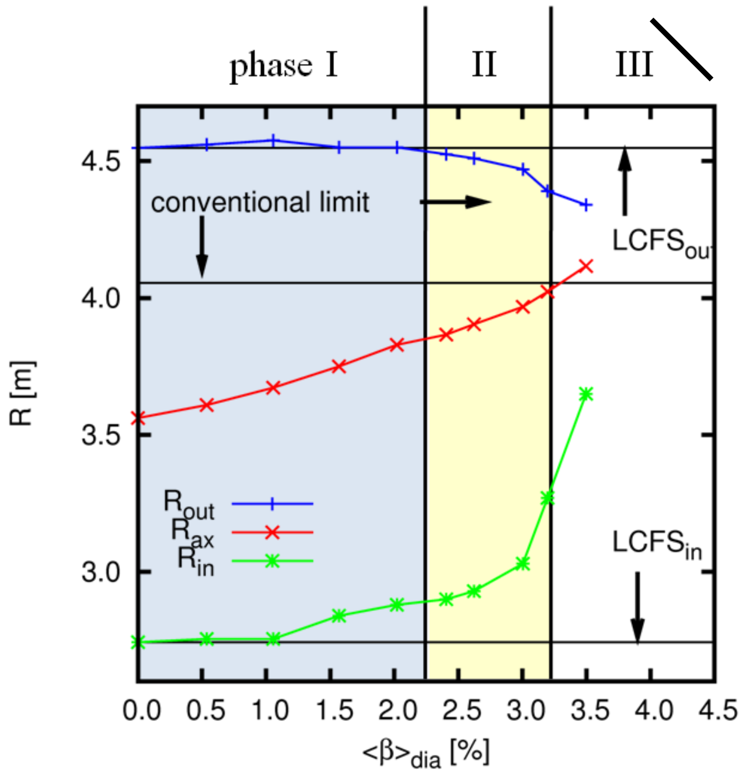


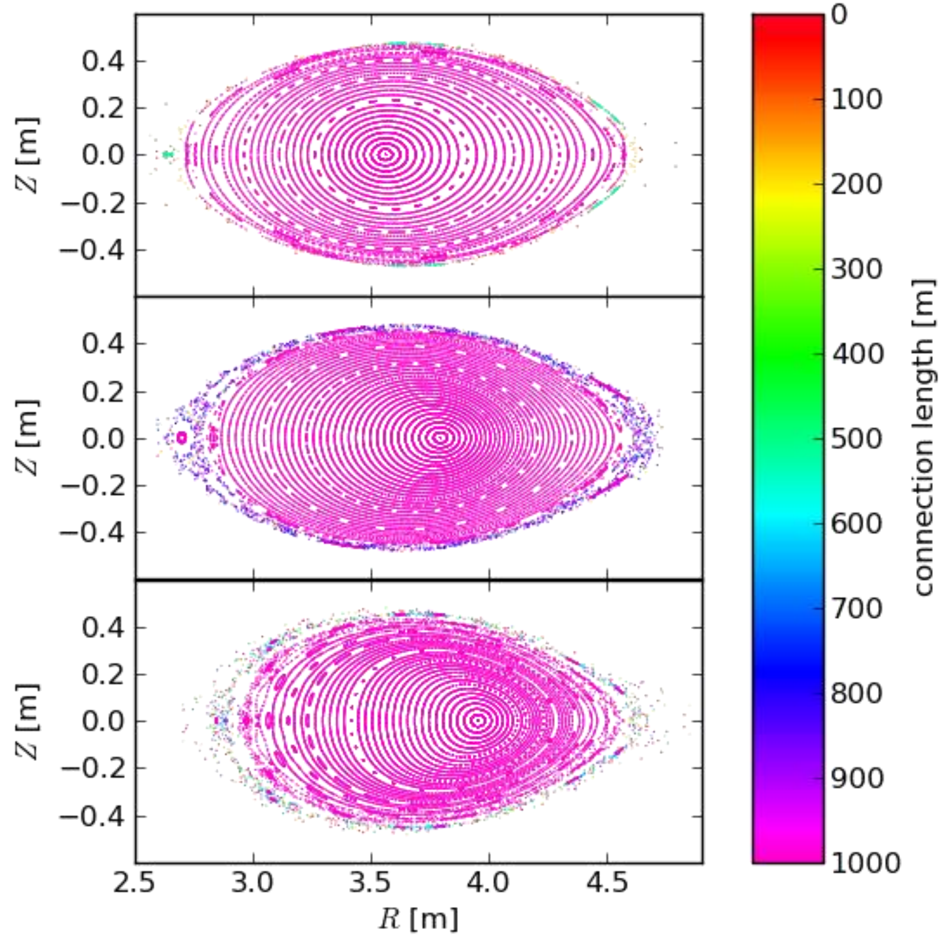

**$R_{ax}$ = 3.6 m, $B_t$ = -0.425 T**



# How about is the magnetic surface topology?

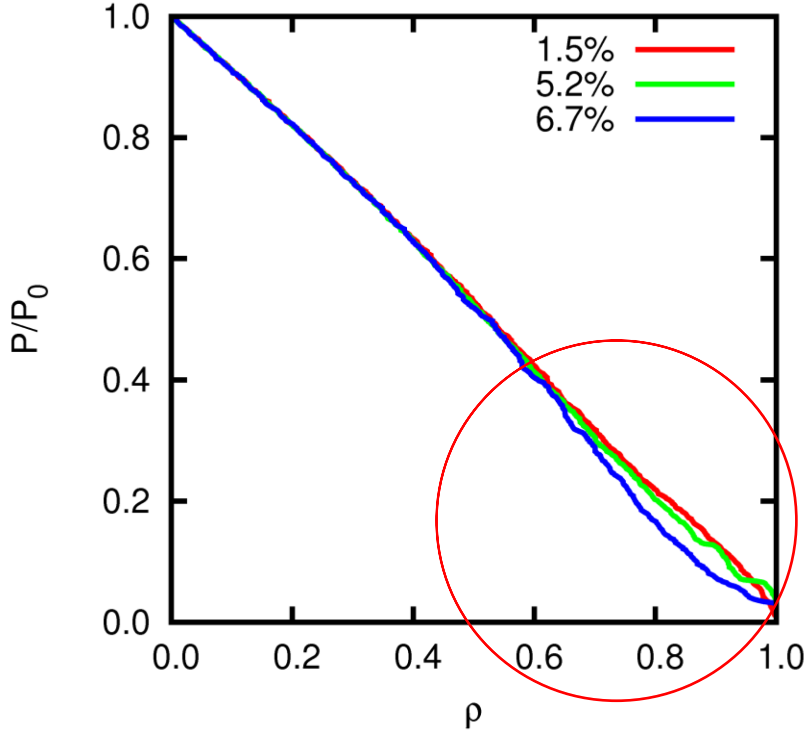
Degradation of flux surfaces due to increasing β



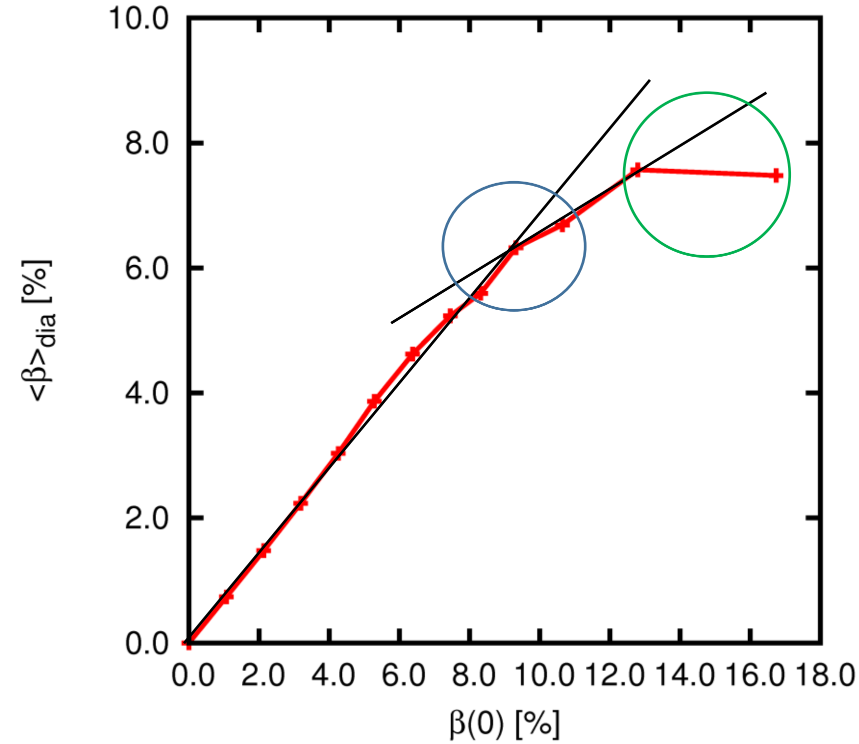




In the peripheral region, magnetic field lines become stochastic as b increases.
The volume inside LCFS shrinks drastically.

# Results of HINT analyses




For β>6.7%, the fixed pressure profile is reduced at ρ>0.6.



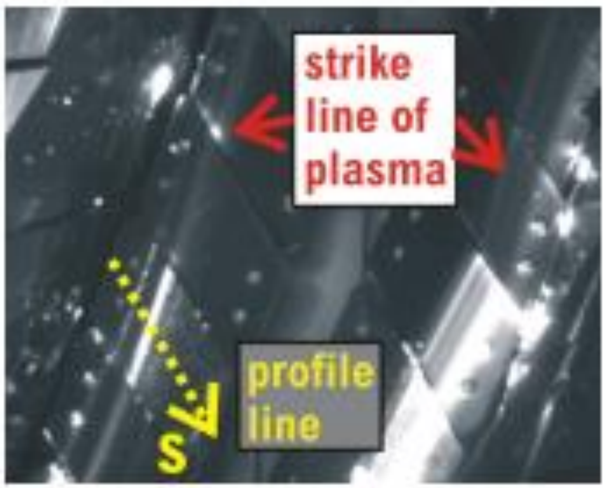

The slope of <β> changes due to the reduction of the pressure profile.

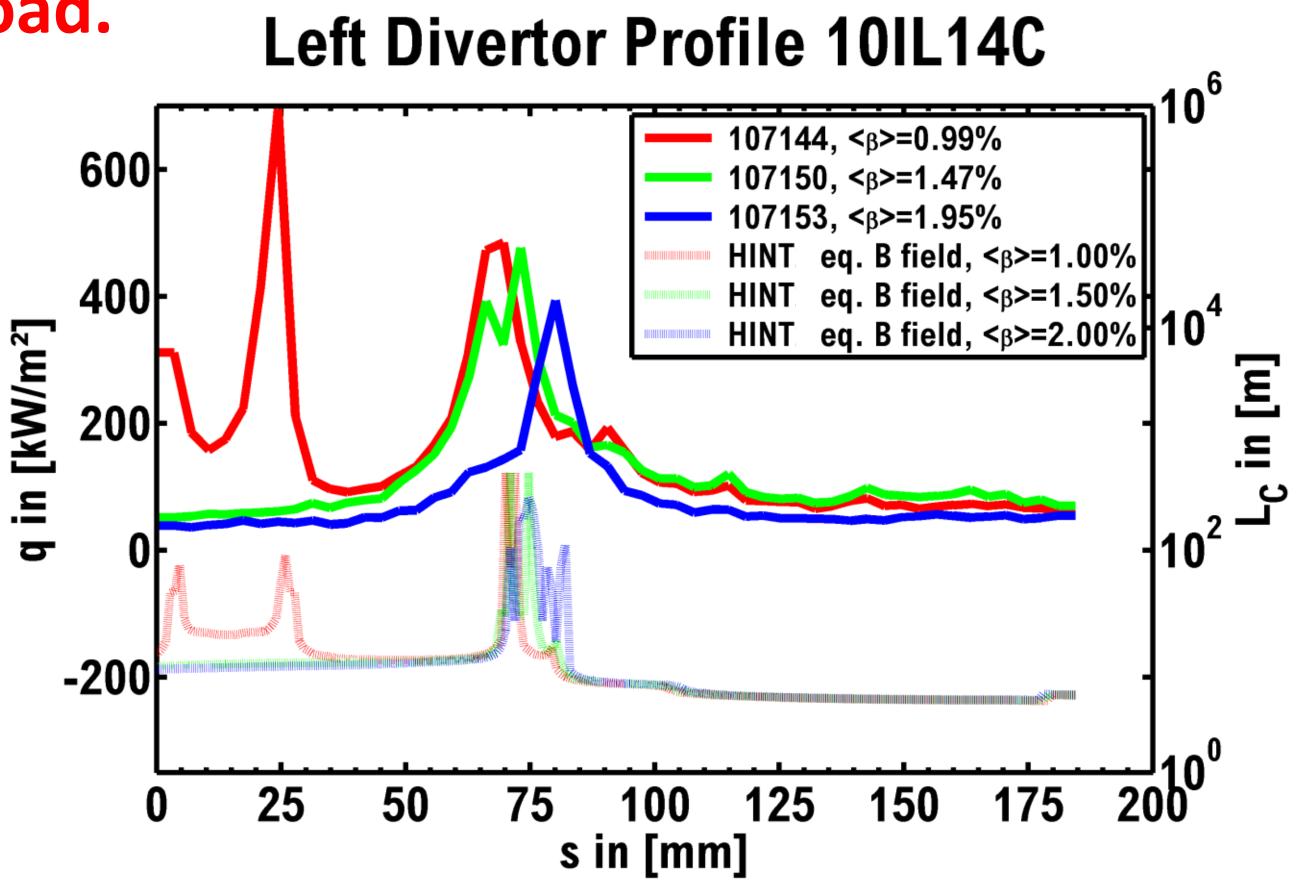
**The change of the slope is a good index of the equilibrium beta limit.**
**Note: this index is a soft limit of the MHD equilibrium.**

# Heat flux strongly depends on magnetic topology

**Stochastization of magnetic field lines strongly affects on divertor heat load.**

In LHD, divertor heat load was measured by IR camera system.

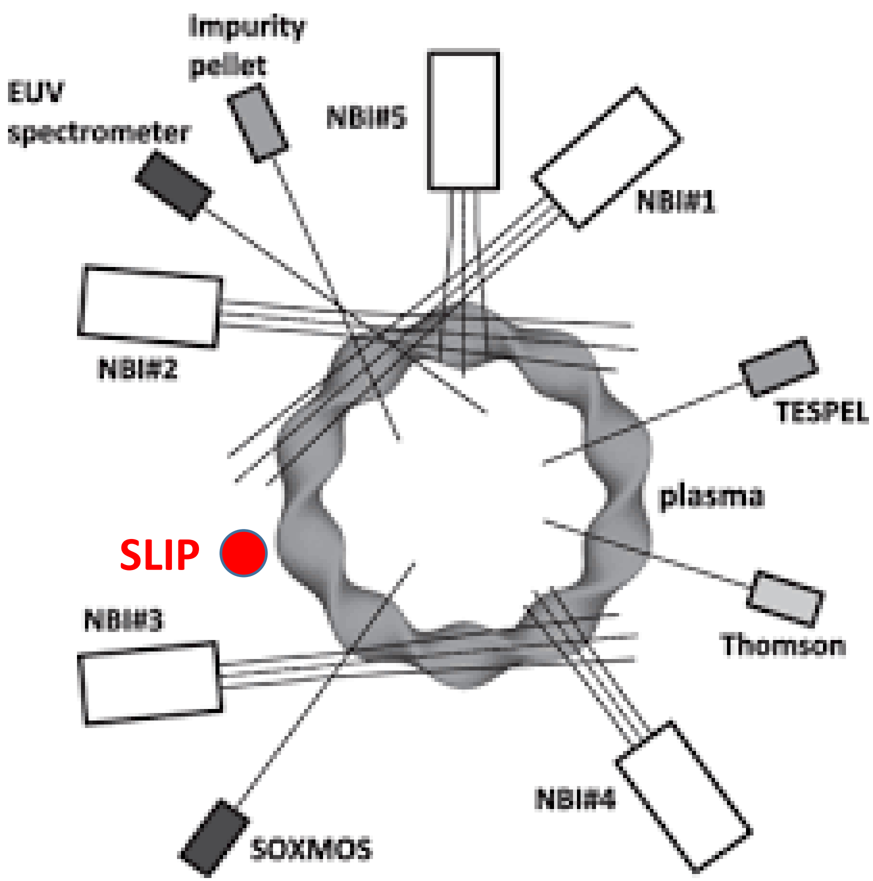


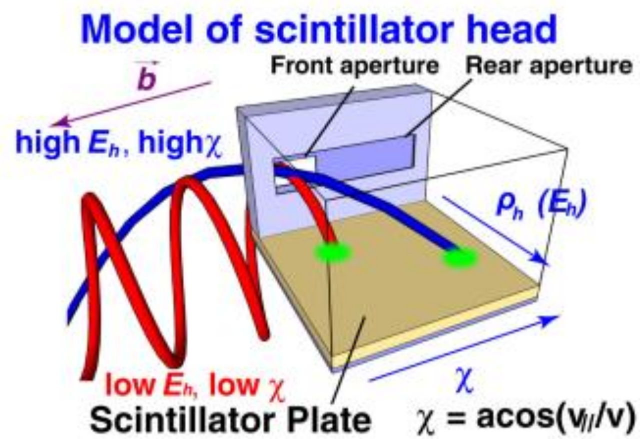



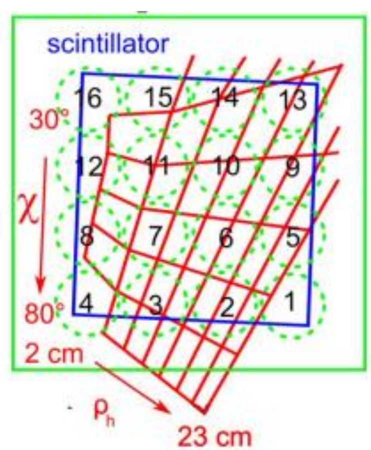

**HINT can give reliable prediction!**

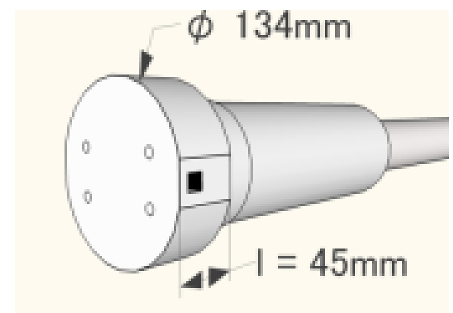
# Fast ion orbit is very sensitive to magnetic topology

**Scintillator-based Lost Ion Probe (SLIP) is installed to measure fast ion loss.**



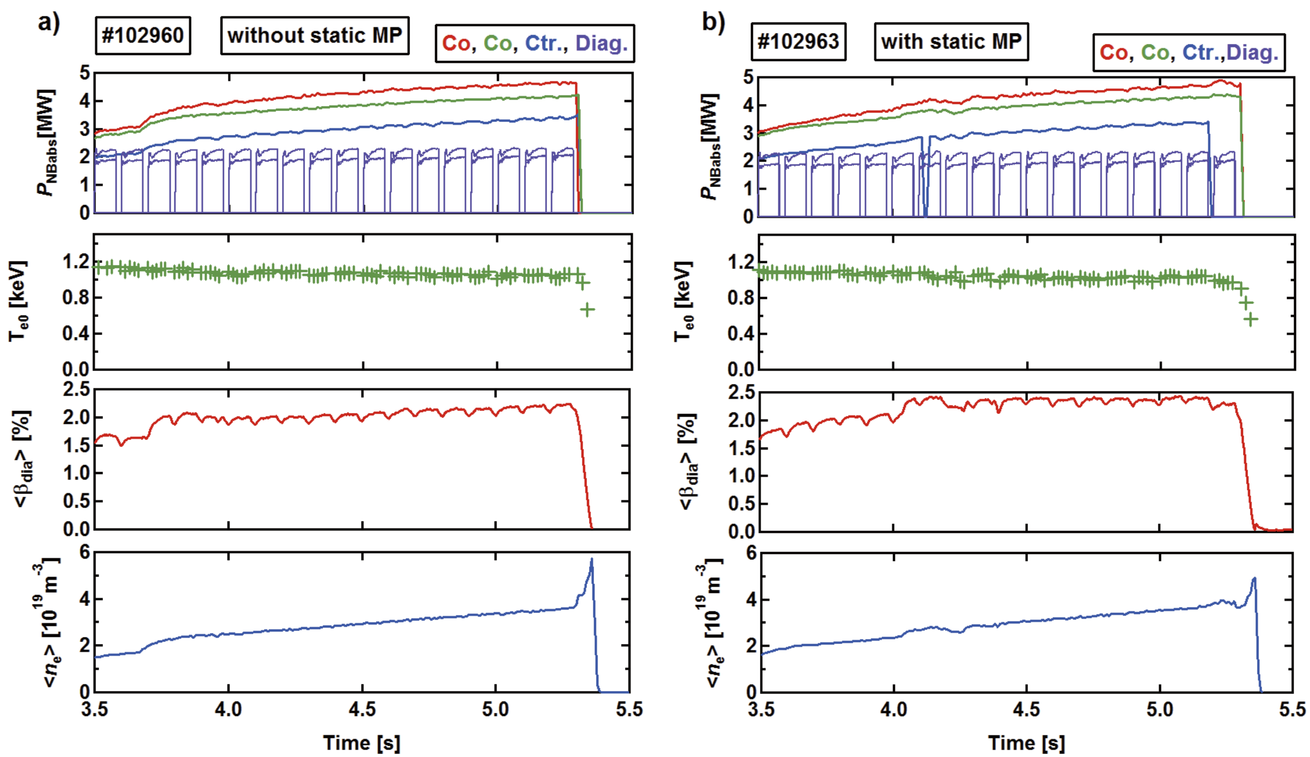



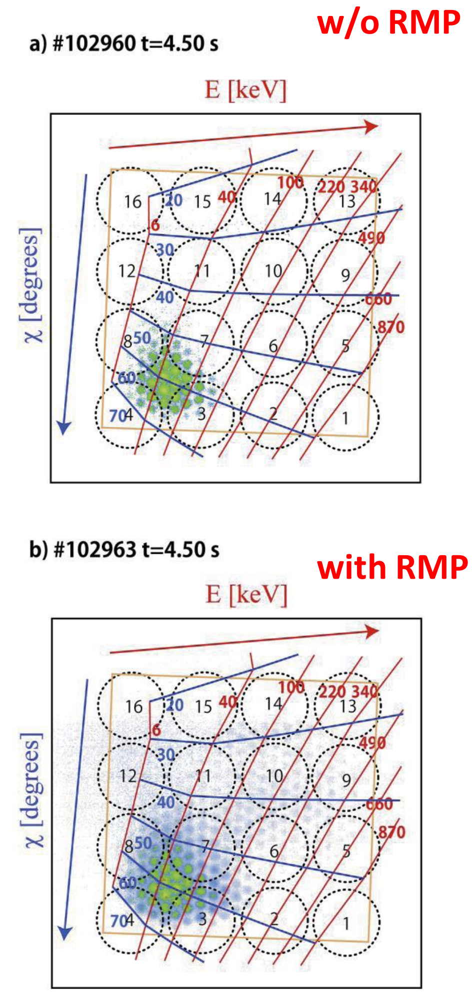



# RMP experiment in LHD

## Standard configuration (Rax=3.6m), B=-0.9T




Scintillator image (SLIP, 8-O)

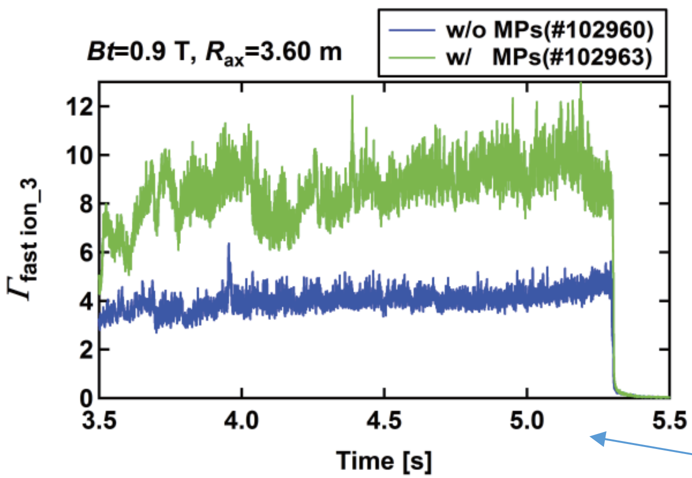


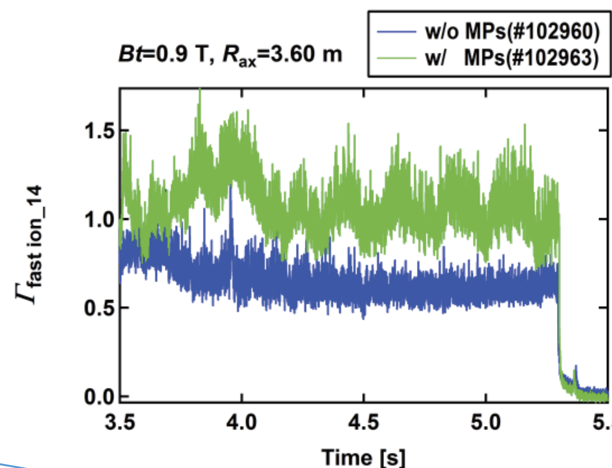

**Almost same shots could be reproduced with and w/o RMP.**

# RMP experiment in LHD

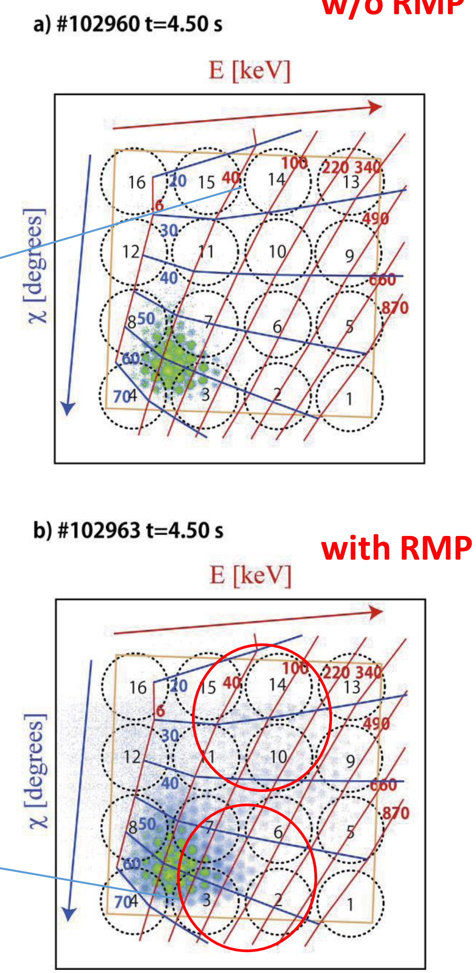
**Time evolutions of fast-ion-loss signals measured by SLIP at PMT 3 and 14.**

**RMP enhances fast ion loss.**



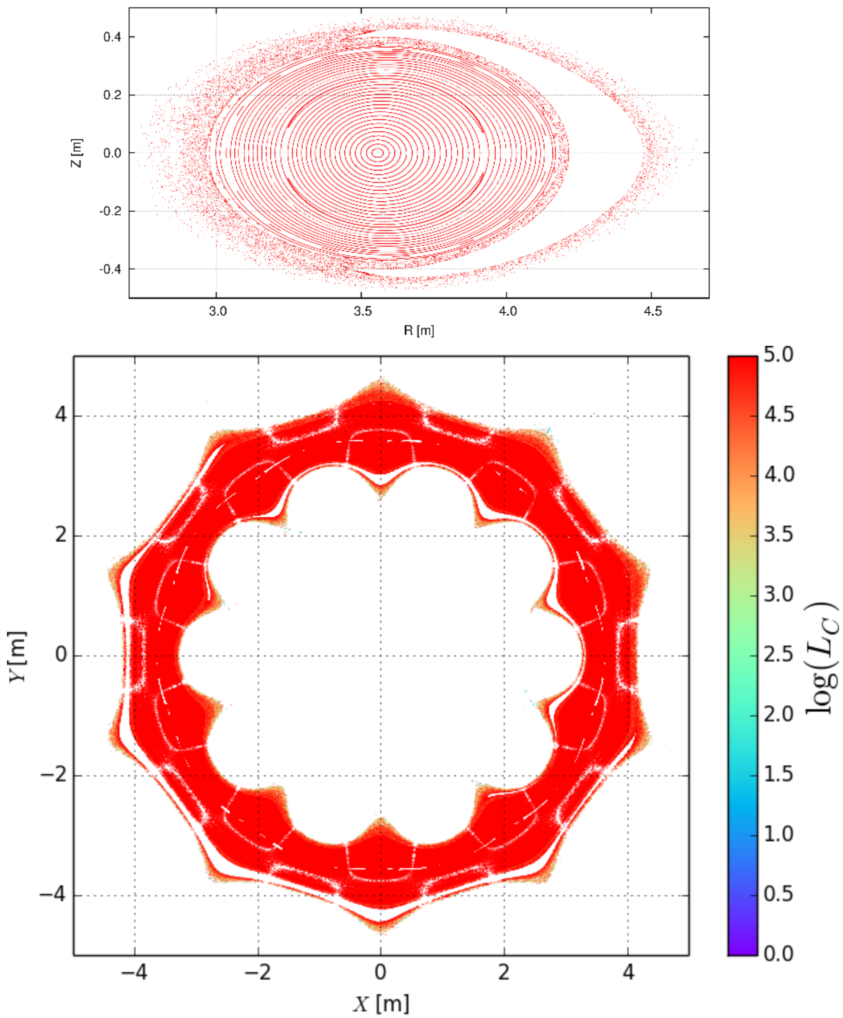

**Scintillator image (SLIP, 8-O)**



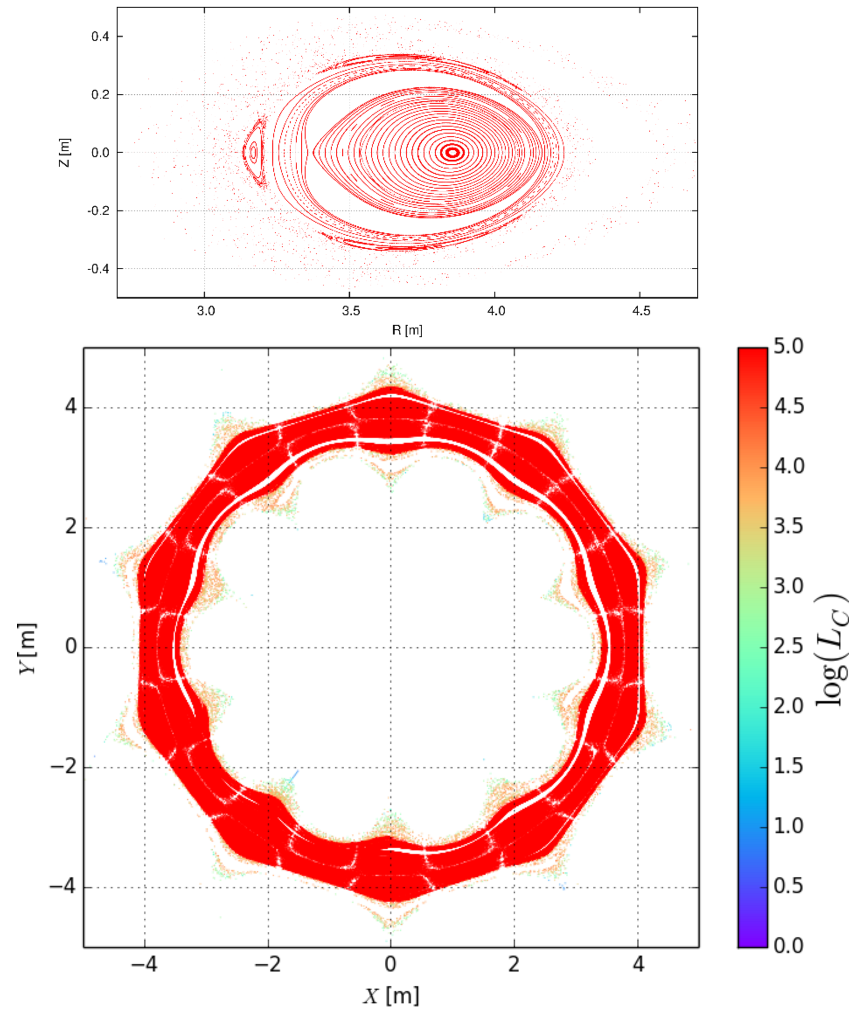

- **Low-pitch angle/high energy loss increases.**
- **High-pitch angle/low energy loss increases.**

# Impact of beta effects on magnetic topology

vacuum

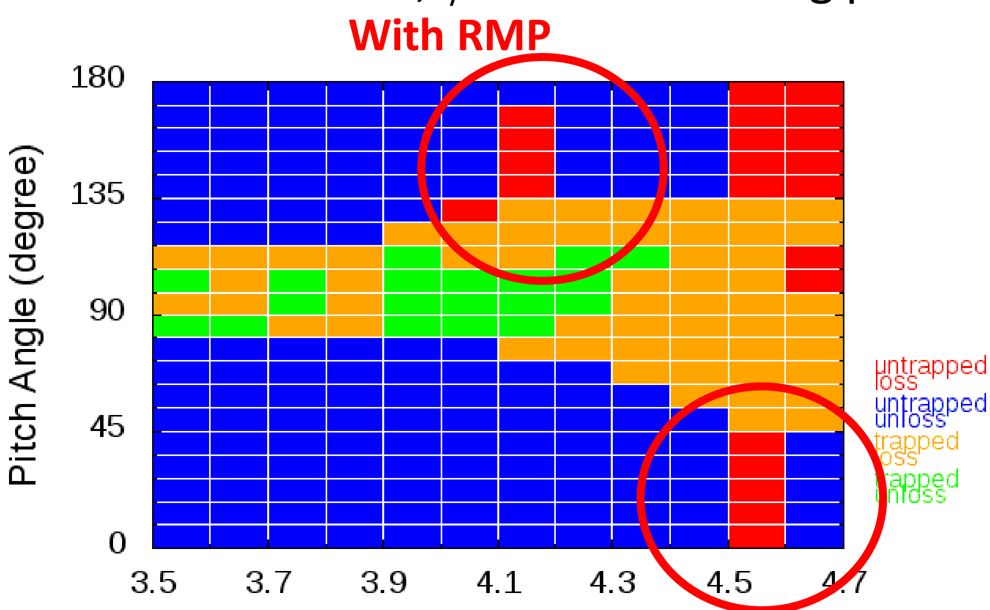


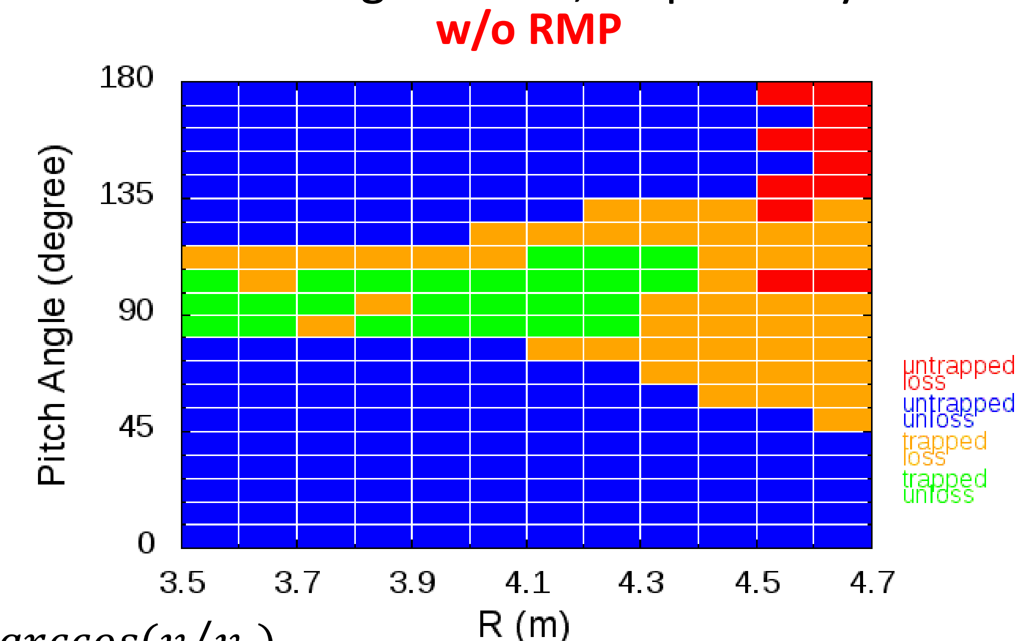

<β> ~ 2.4%



# Impacts of RMP on fast ion confinement

To study impacts of RMP qualitatively, collisionless orbit of fast is studied.
$E$ = 90keV, $\phi$ and $Z$ of starting point are fixed to 234 deg and 0 m, respectively.




Pitch angle, $\chi = arccos(v/v_{\parallel})$

**Because of RMP…,**

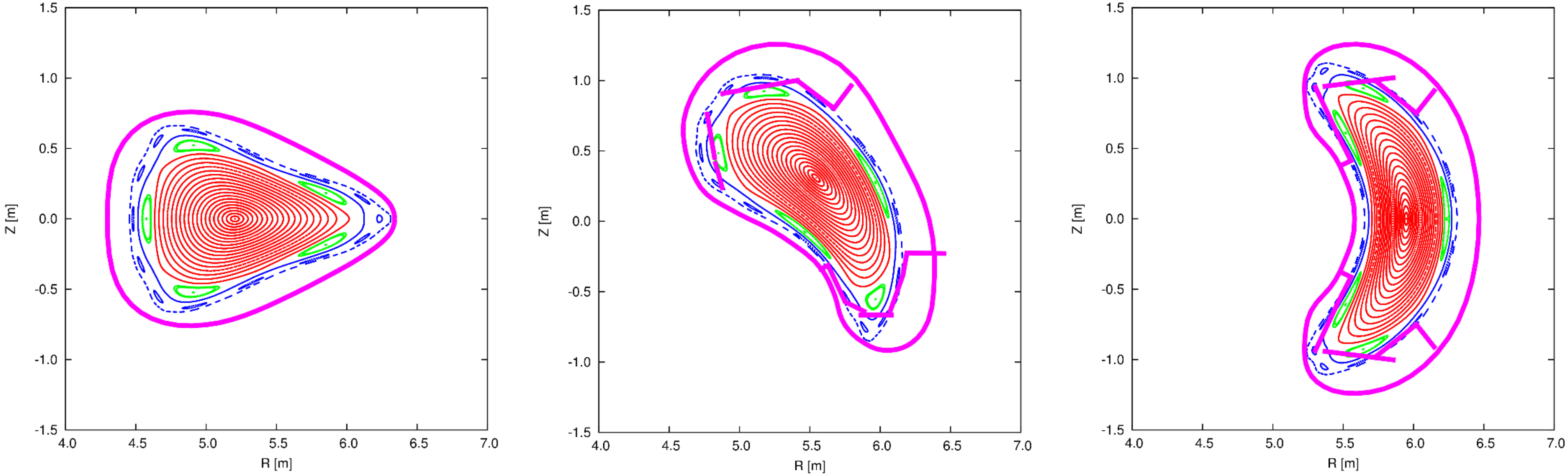
1. **Loss of passing particles starting from R ~ 4.5 m (Co) and R ~ 4.1 m (Cntr) is increased.**
2. **Loss of trapped particle starting from R ~ 4.1m is increased.**

**These are consistent to SLIP observation.**

**Courtesy to J. Morimoto**

# Wendelstein 7-X
# - Island divertor concept -

**Island divertor: small pitch allows use of perpendicular transport of magnetic islands.**

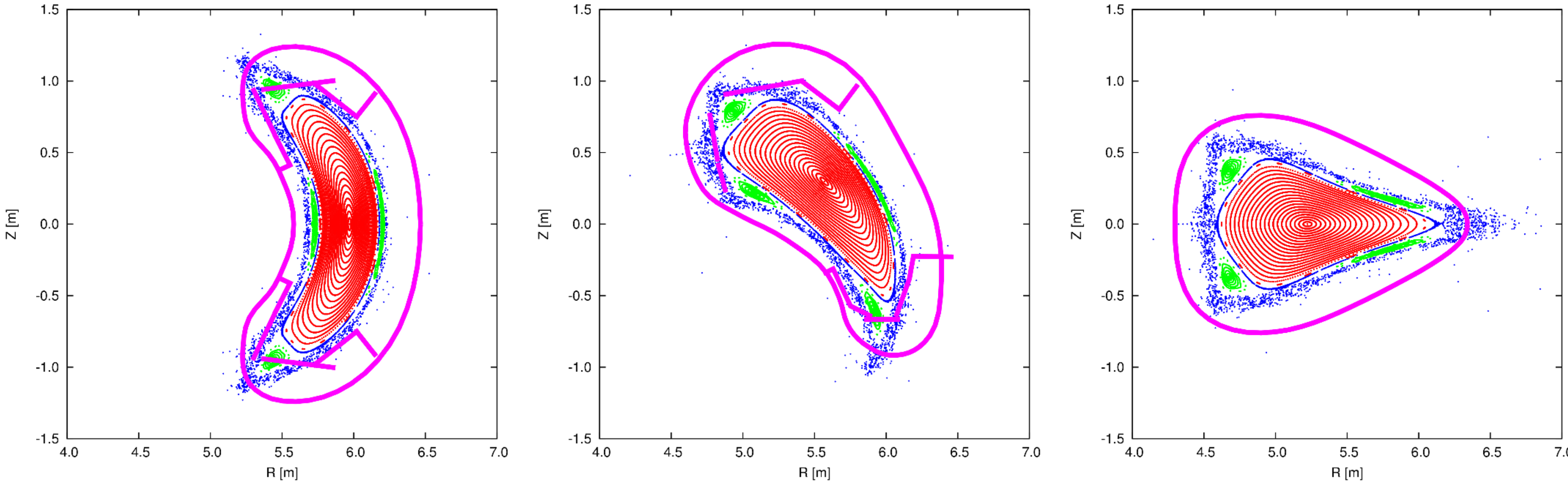



- **Optimization of W7-X: MHD-equilibrium, stability, … but not for divertor!**
- **Natural islands used for separatrix generation to divert fluxes to appropriately designed divertor plates!**
- **Low shear: Islands generated with small field components ($B_r/B$ ~ 10-4)!**

**Divertor configurations are very sensitive plasma generated fields!**
**(e.g. beta-effects and net-toroidal current densities)**

# High-iota configuration
# - magnetic field configuration -

**Divertor islands at iota = 5/4**



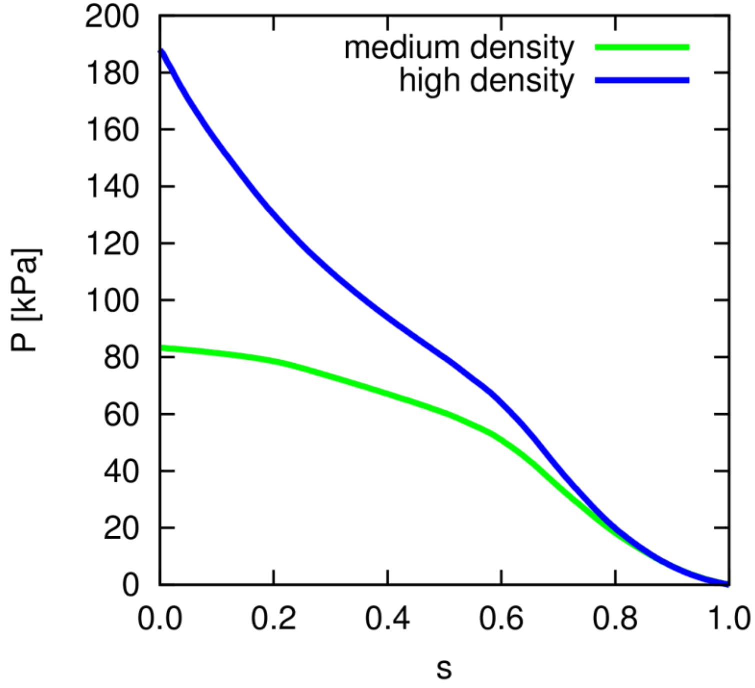

**Strong stochastization is expected.**

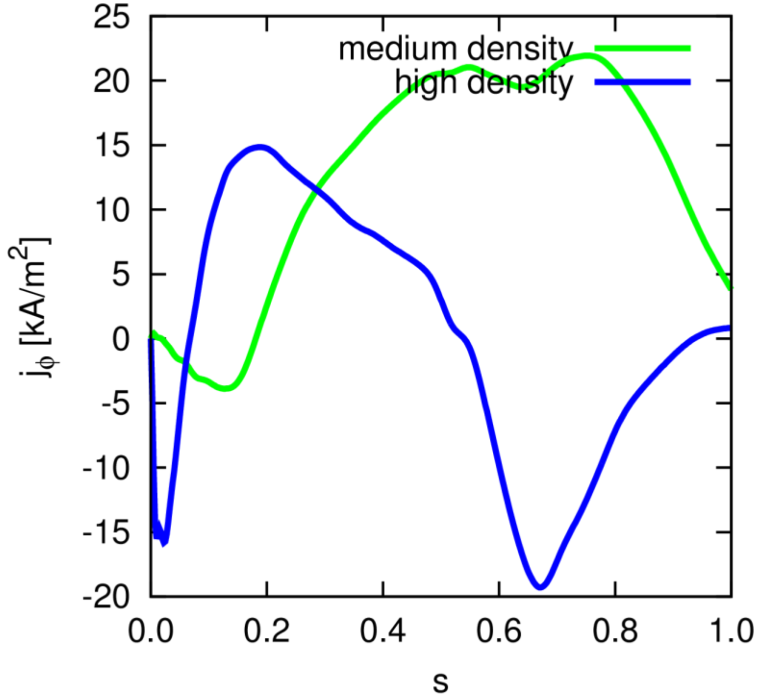
1. **E. Strumberger, et al., in Nuclear Fusion**
2. **Y. Suzuki, et al., in EPS2006**

**But, the toroidal current density effect not yet studied.**

# High-iota configuration
# - pressure and current density profiles -

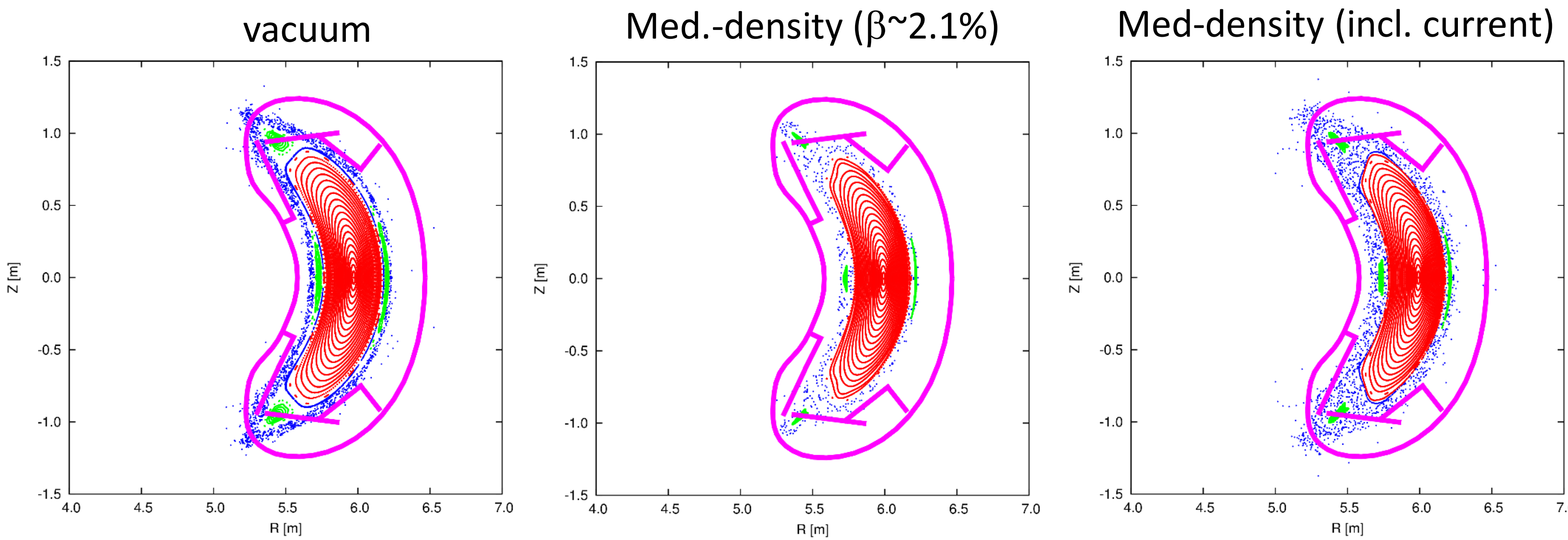
**Radial profiles predicted by the self-consistent transport analysis**



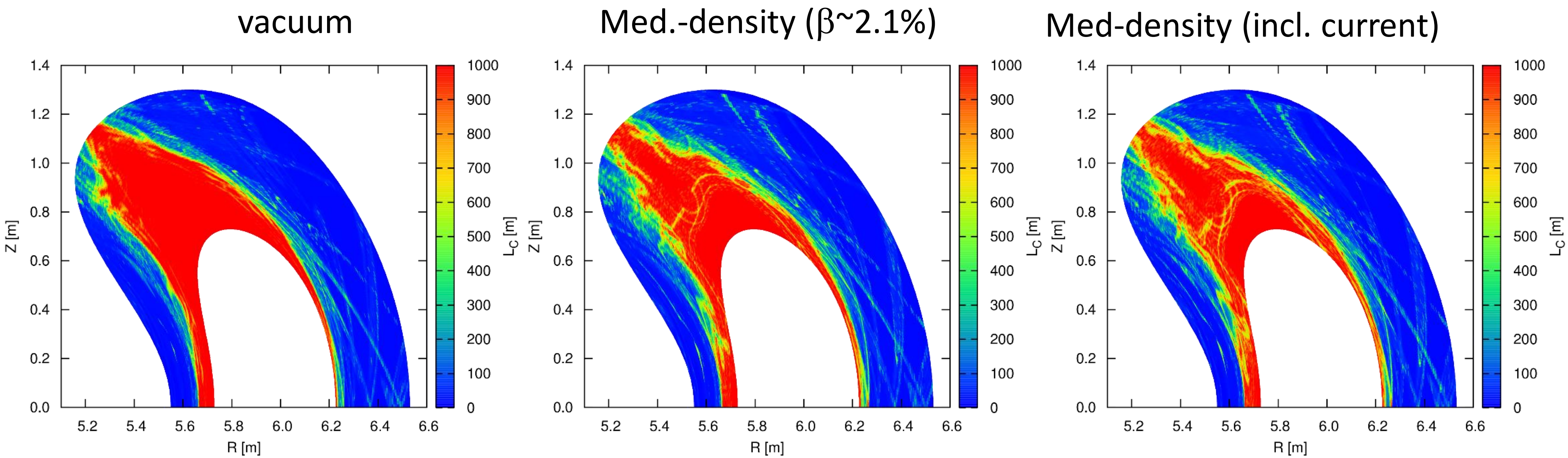

- **Low to high density => broad to more peaked (<=> off- to on-axis heating).**
- **Electron-root for low and medium density => enhanced bootstrap current density**
- **High density => small bootstrap current densities (Ip < 1kA).**

# Impacts of β-sequence and current density - magnetic field configuration -




- **5/4 islands are robust up to 3%. But, increasing stochastization.**
- **Higher-order rational islands grow and overlap (e.g. 15/13) => volume shrinks.**
- **Toroidal current densities can shrink island sizes of high-order rationals but enhance stochasticity.**
- **For high-density case, 5/5 islands appear in plasma core(beta + bootstrap current density).**
- **higher elongation of flux surfaces => less tight fitting divertor**

# Impacts of β-sequence and current density - magnetic field configuration -

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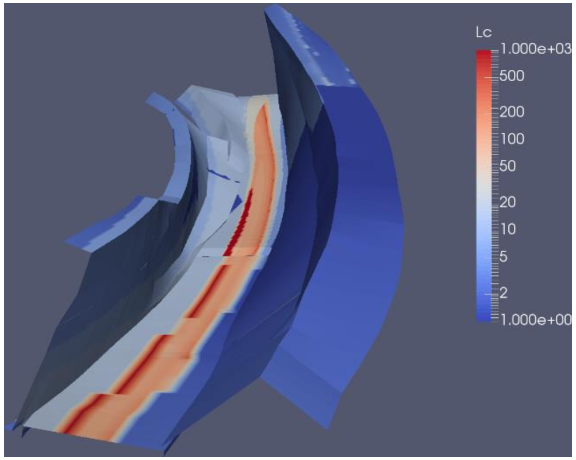
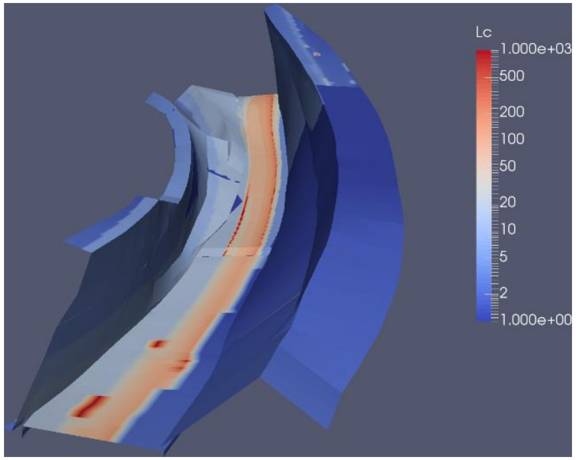
- **higher elongation of flux surfaces => less tight fitting divertor**

# Impacts to divertor operation
# - footprints onto in-vessel components --

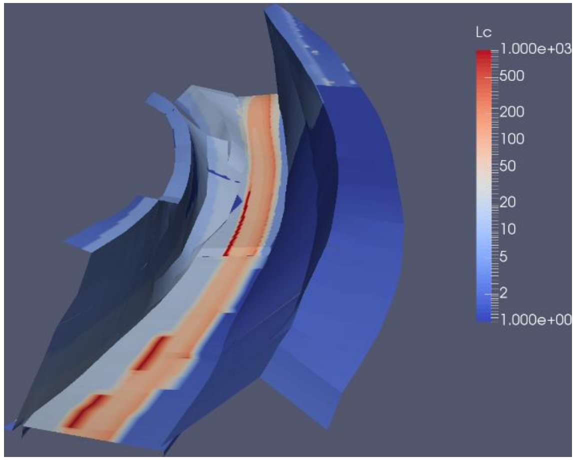
**vacuum**




**Medium density**




**Medium density incl. current**

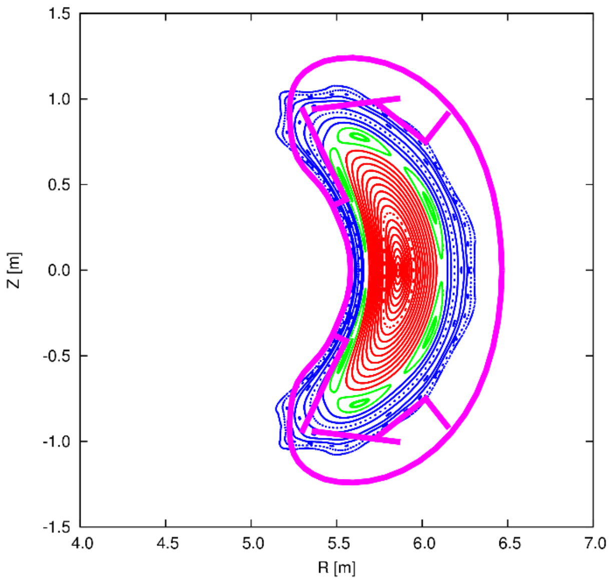



- **For vacuum case, plasma is diverted onto in-vessel components.**
- **For medium-density case, connection length becomes short because of enhanced stochasticity.**
- **For including current density, plasma is still deiverted by in-vessels and new splitting appear.**

# Minimum bootstrap current configuration at low-iota

**Minimum bootstrap current at low-iota <==> large toroidal mirror field $b_{01}$≈24%**

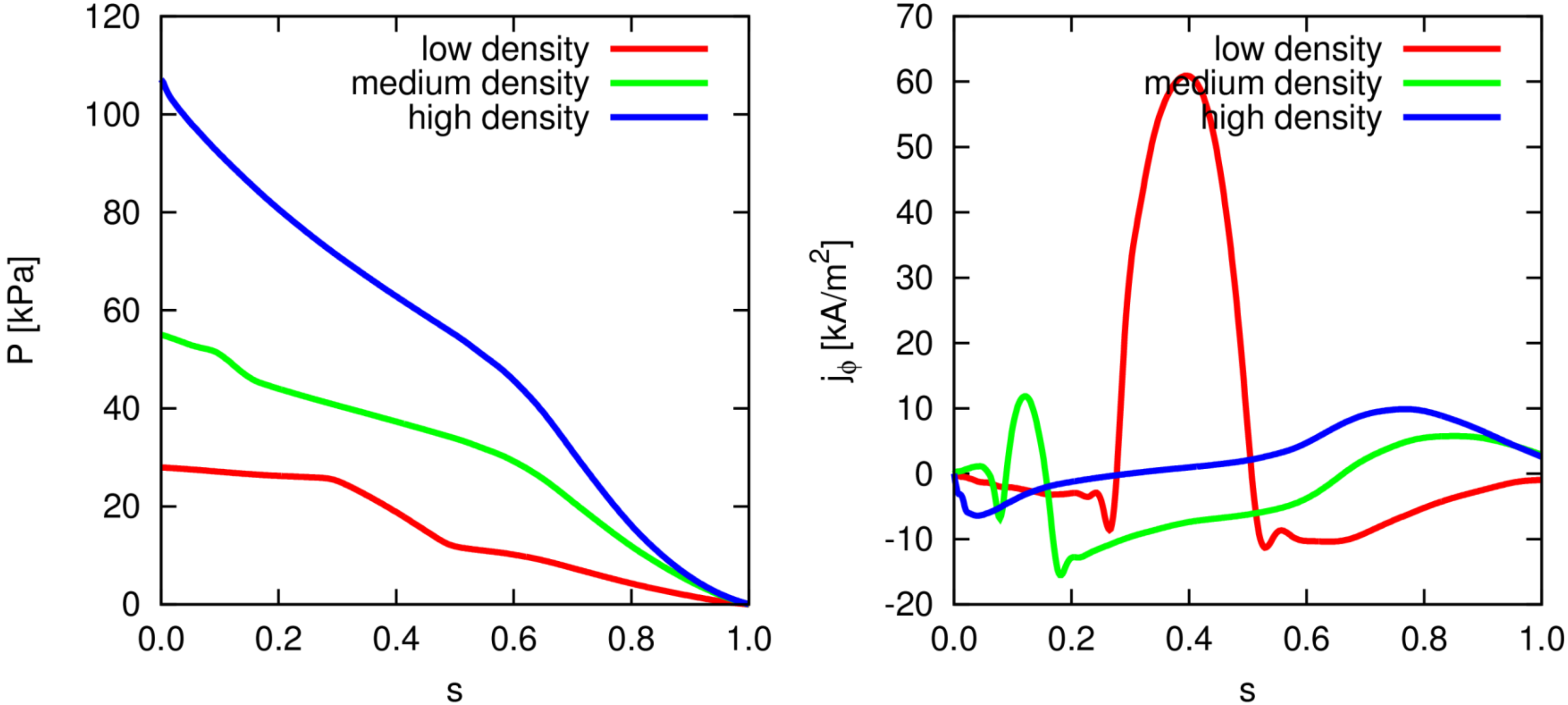
**Divertor islands at iota = 5/6**




- **Strong toroidal variation of cross section due to large mirror field**
  **small cross section in bean-shaped plane**
  **divertor interaction around phi=16° (teardrop cross section)**
  **divertor geometry adapted for mirror fields from 0% to 10%**
- **Self-consistent transport simulations focussed on core confinement (J. Geiger, et al., EPS2014). Adjustments of configuration might be needed for divertor compatibility.**

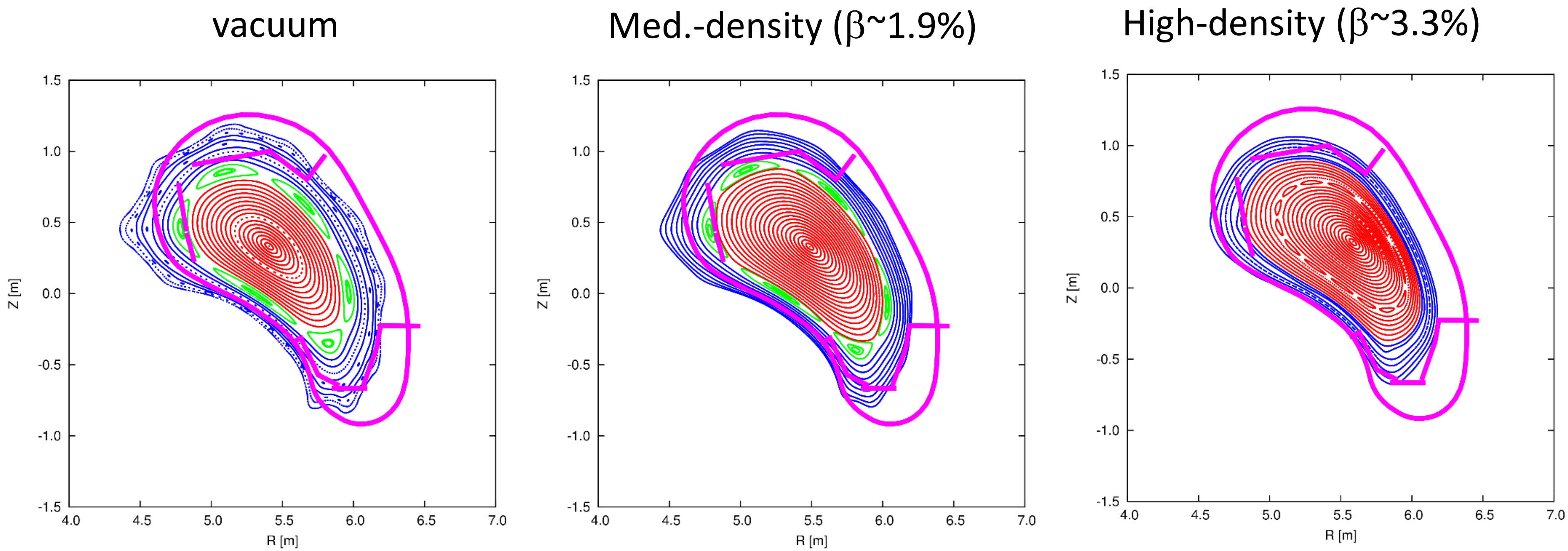
# Low-iota configuration
# - pressure and current density profiles -

**Radial profiles predicted by the self-consistent transport analysis**




- **Low to high density => broad to more peaked (<=> off- to on-axis heating).**
- **Electron-root for low and medium density => enhanced bootstrap current density**
- **High density => small bootstrap current densities (Ipl < 2kA).**

# Impacts in β-sequence
# - magnetic field configuration -



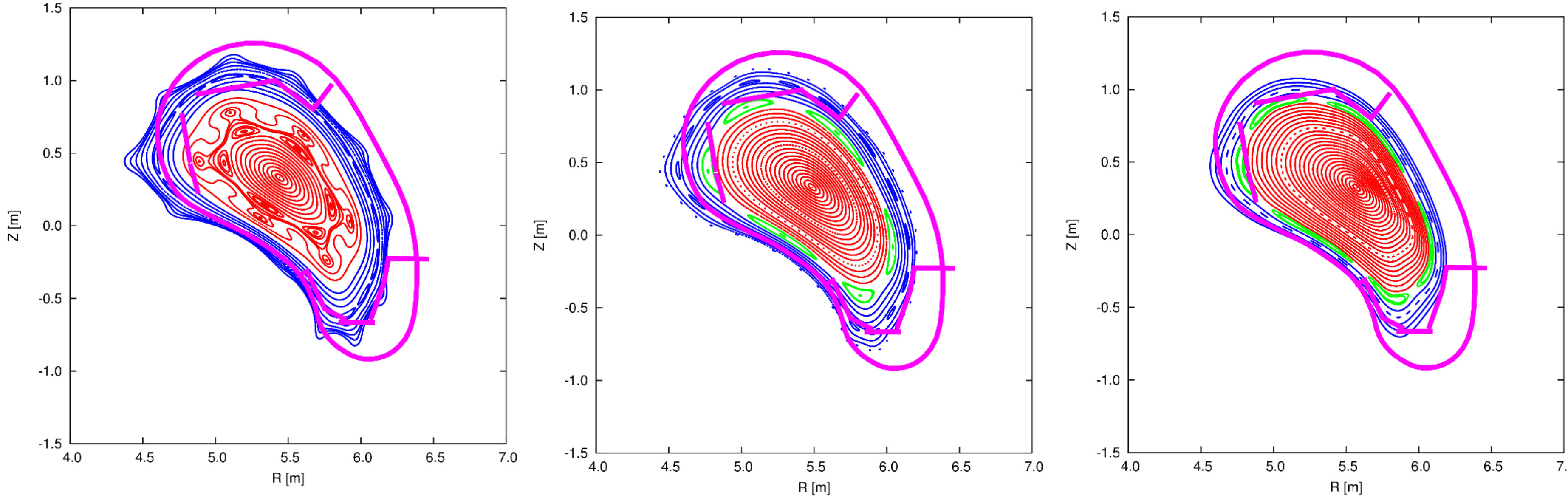

- 5/6 islands are robust for vacuum and low density cases.
- Medium density case => 5/6 Islands shift radially outward => Limiter configuration.
- High density case => 5/6 islands vanish (self-healing), 10/12 islands become visible.
- Plasma is limited by vertical baffle plate in all cases.
- Flux surfaces fill divertor volume rather tight.

=> configuration adjustment with planar coils: horizontal positioning, iota-fine-tuning?

=> control 5/6-island width by sweep coils?

# Impacts of toroidal current density - magnetic field configuration -

Low-density (β~0.9%) Med.-density (β~1.9%) High-density (β~3.3%)




**Current density profile from transport simulation**

**5/6 islands are robust.**

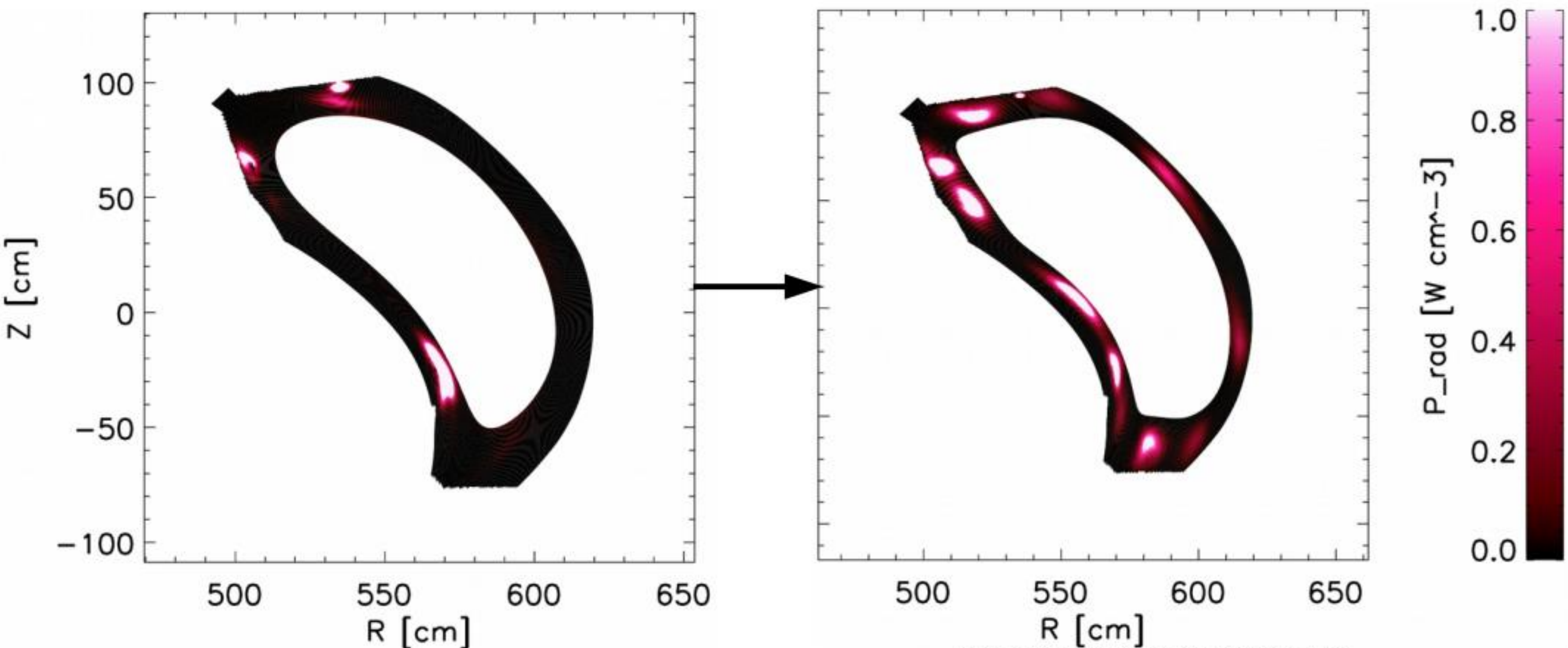
**Radial location of 5/6 islands moves according to current densities**

- **low density: islands inside due to localized bootstrap current density**
- **medium + high density: islands at boundary, but smaller for high-density**

**Positive current => diverted, negative current => limited**

# Equilibrium effects seem to cause more homogenous radiation distribution

→ beneficial effects for radiative mantle?



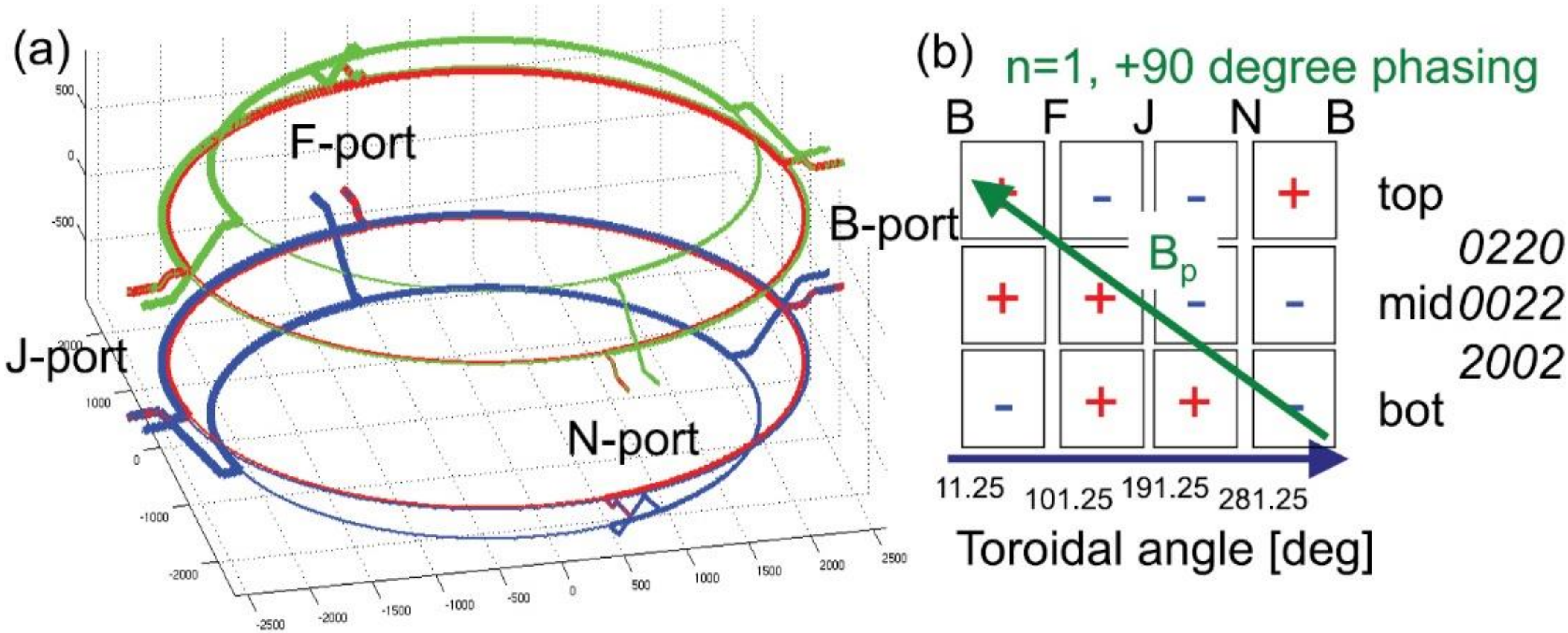

(HINT2 equilibrium: courtesy of Y. Suzuki)

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

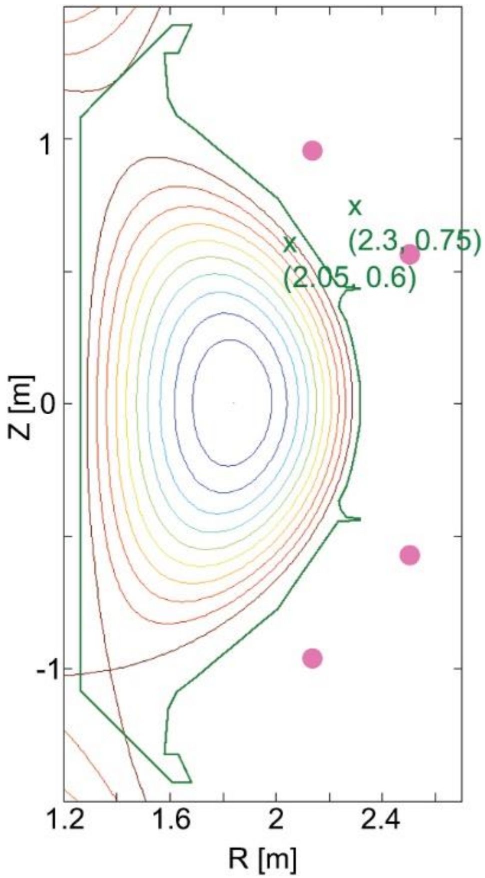
F. Effenberg, 16th Coordinated Working Group Meeting, Madrid, 2017

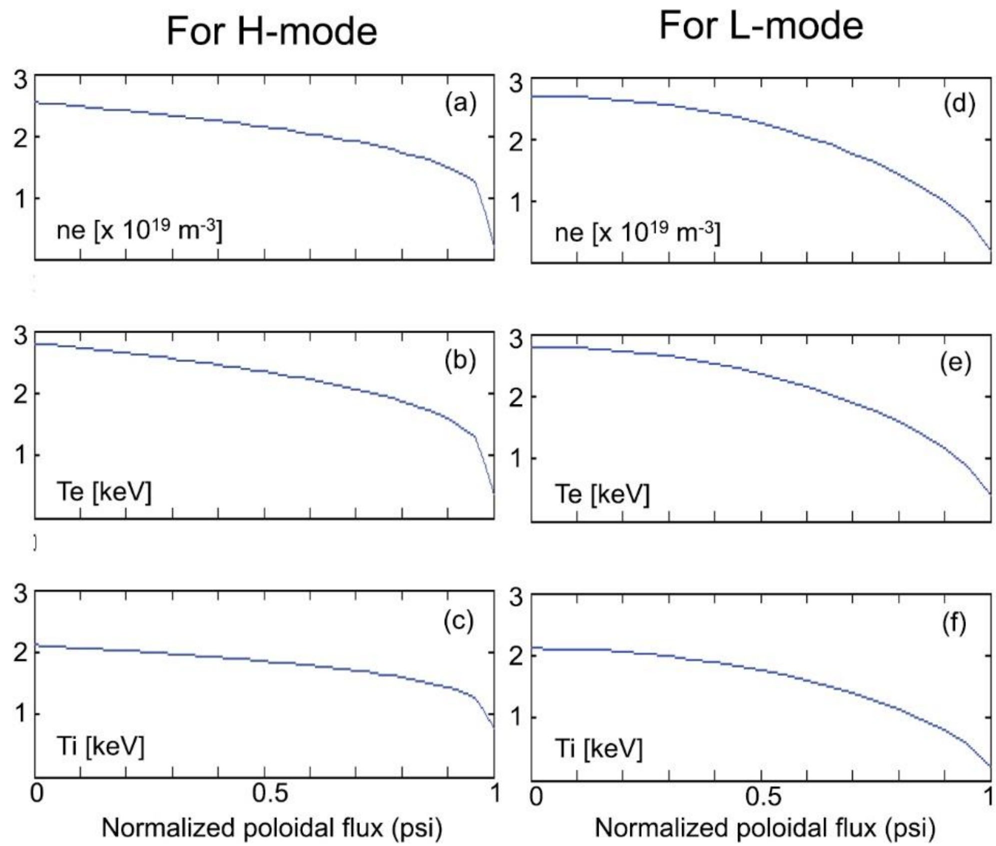
# Impact of RMP on magnetic topology in KSTAR

## RMP coils model



# Nonlinear response studied for 2 scenarios (H- and L-modes)

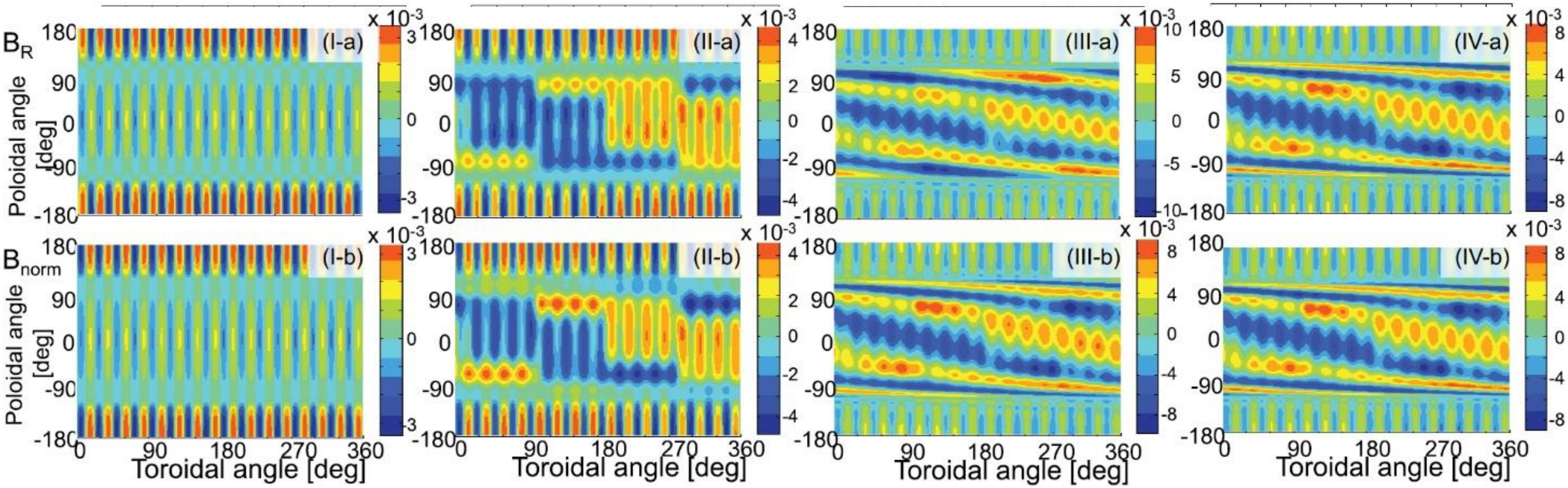



- ITER-like LSN configuration is studied.
- Plasma profiles are modeled artificially.

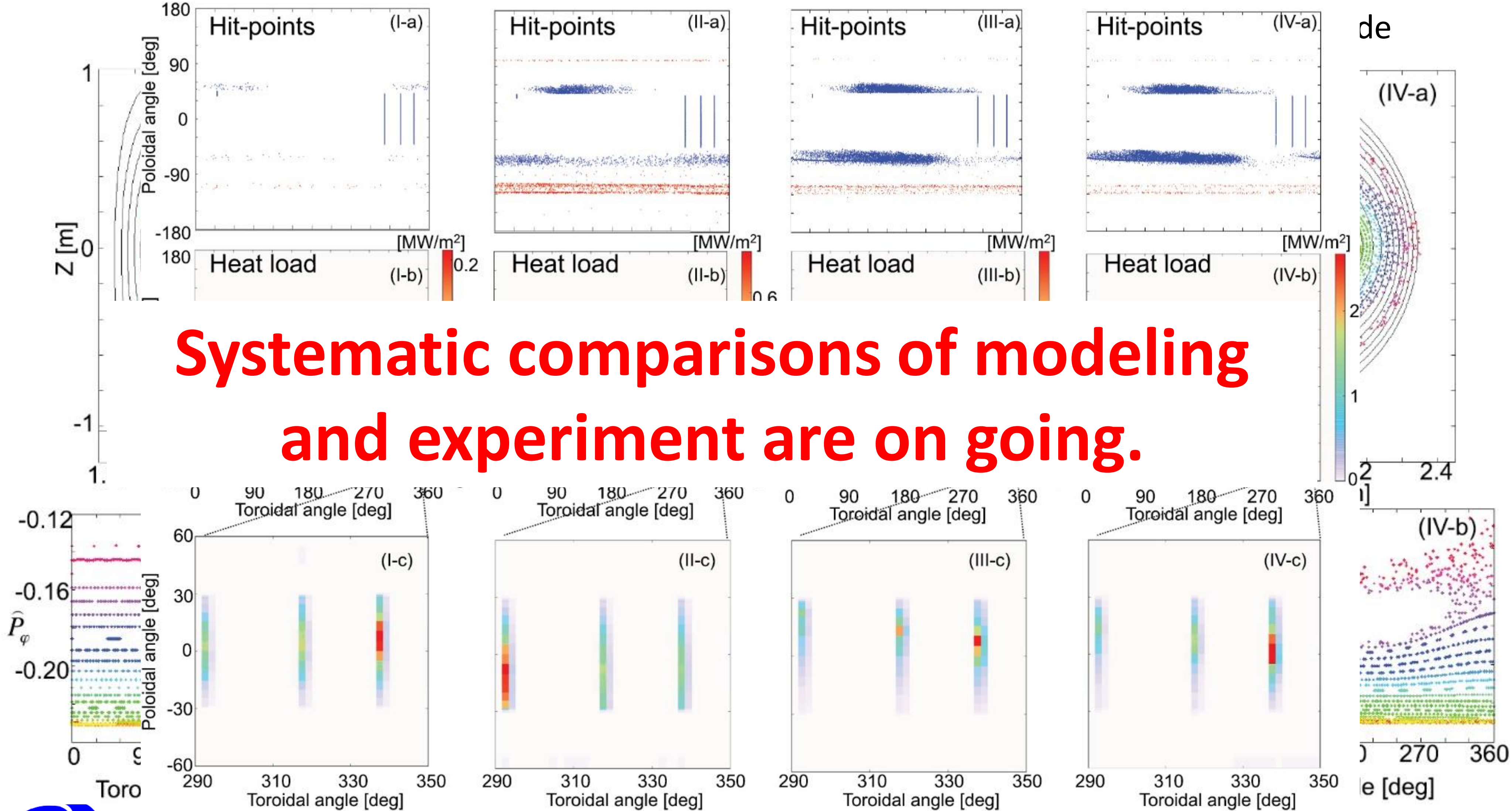
# Magnetic field variation in different model and profiles

**TF ripple only** **Vacuum model** **HINT (H-mode)** **HINT (L-mode)**




- **Step-like n=1 pattern appeared for vacuum approximation.**
- **Smooth n=1 pattern appeared for HINT, because n=1 RMP makes helical distortion of plasma column.**

# Topological change seems small for L- and H-mode cases, but…




**Systematic comparisons of modeling and experiment are on going.**

# Contents

# Impact of plasma rotation on 3D MHD equilibrium

**In many experiments, the plasma rotation is observed.**

**To simulate more realistic 3D equilibrium, the rotation should be included. And, the impact of the rotation to the magnetic field is interesting.**

- **Assuming only toroidal rotation.**
- **Assuming isothermal condition.**
- **If the toroidal plasma rotation exists, the pressure distribution is shifted by the inertial force.**

$$p \equiv p_0(\Phi) \exp\left[ M^2 \left( \frac{R^2}{R_0^2} - 1 \right) \right]$$

**Here,**

$$M^2(\Phi) \equiv \left( \frac{v_\phi}{v_{th}} \right)^2 = \frac{m_i R_0^2 \Omega^2}{2T}$$

# Improvement of HINT to include plasma rotation

$$
\begin{aligned}
\frac{\partial \mathbf{v}_1}{\partial t} &= -\mathbf{v}_0 \cdot \nabla \mathbf{v}_0 - \nabla p + \mathbf{j} \times (\mathbf{B}_0 + \mathbf{B}_1) + \mu \Delta (\mathbf{v}_0 + \mathbf{v}_1) \\
\frac{\partial \mathbf{B}_1}{\partial t} &= \nabla \times [(\mathbf{v}_0 + \mathbf{v}_1) \times (\mathbf{B}_0 + \mathbf{B}_1) - \eta (\mathbf{j}_1 - \mathbf{j}_{\mathrm{net}})] \\
\mathbf{j}_1 &= \nabla \times \mathbf{B}_1
\end{aligned}
$$

**Toroidal flow, $\boldsymbol{v}_0$, is prescribed by the function of the toroidal flux.**

$\rho$ = 1 (constant)

$\boldsymbol{B}$ = $\boldsymbol{B}_0$ (vacuum) + $\boldsymbol{B}_1$ (equilibrium response)

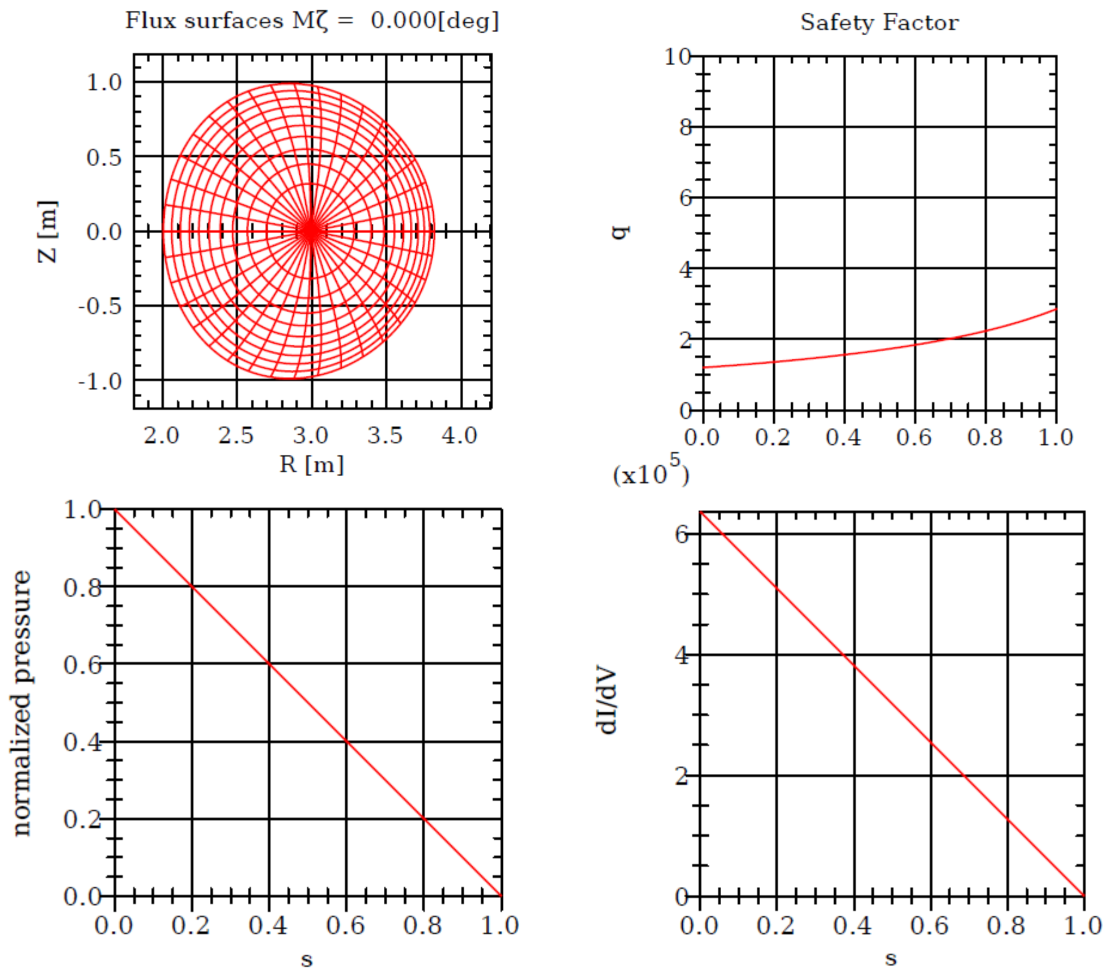
$\boldsymbol{v}$ = $\boldsymbol{v}_0$(given toroidal flow: fixed) + $\boldsymbol{v}_1$ (MHD flow)

$\eta$: resistivity (constant) $\nu$: viscosity (constant)

Collaboration with C. Hegna (U. Wisconsin)

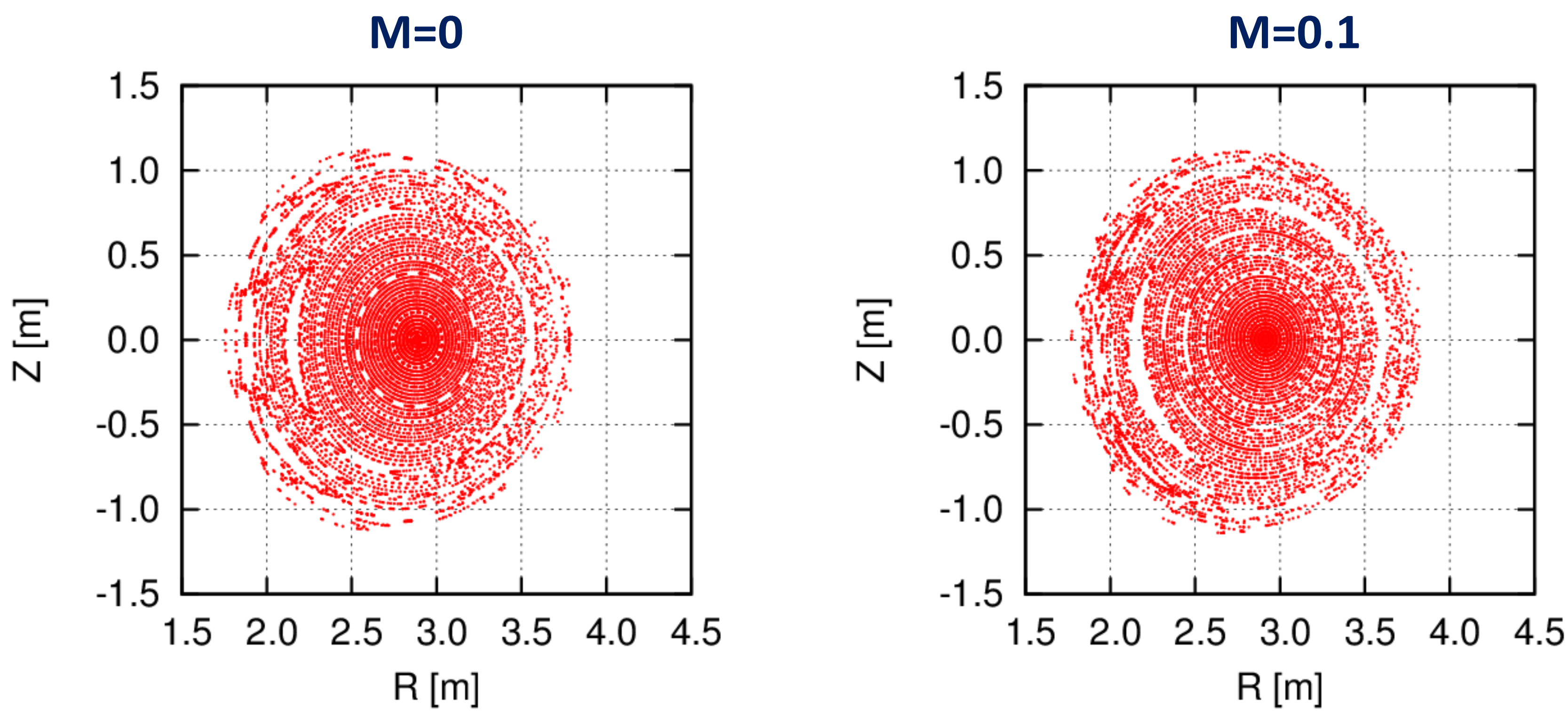
# Impact of plasma rotation on 3D MHD equilibrium

## Reference equilibrium



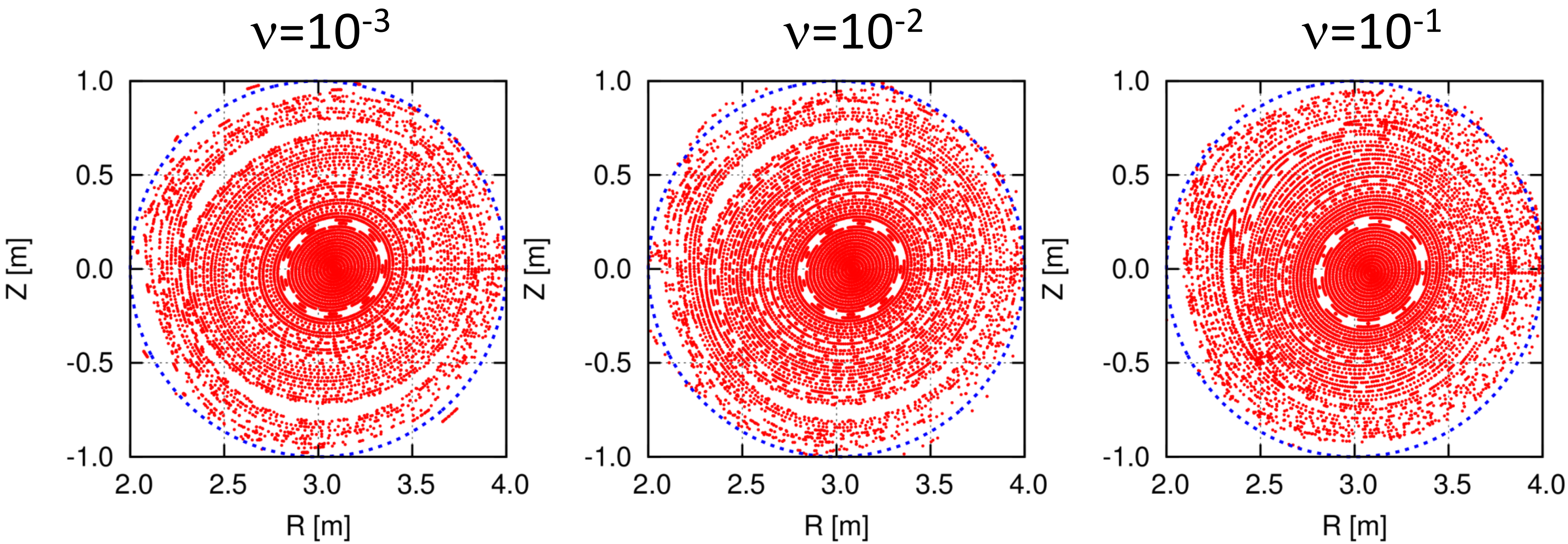
# Impact of plasma rotation on 3D MHD equilibrium

**An example of improved HINT** Y.Suzuki, et al, EPS2016




- **Rigid toroidal rotation is assumed.**
- **Phases of island slips poloidaly.**

# Impact of perpendicular viscosity




- For $\nu=10^{-3}$ and $10^{-2}$, island width and phase are almost identical.
- For $\nu=10^{-1}$, island slips poloidaly, phase changes $\pi$. But, island healing is healed.

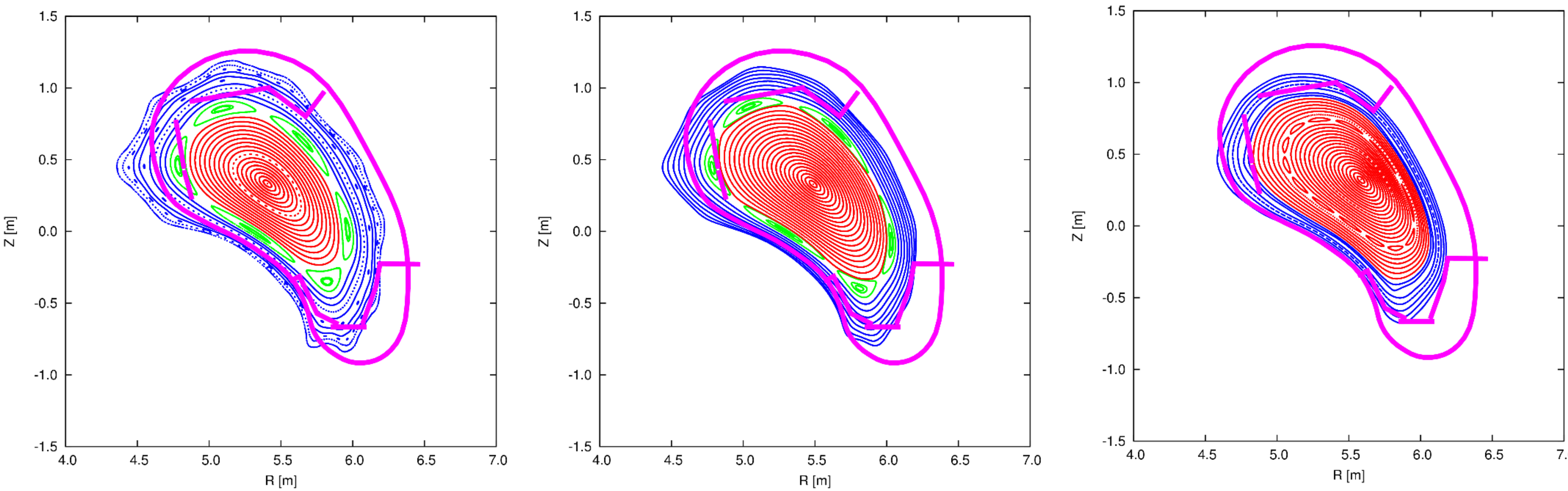
# Contents

# Summary and outlook

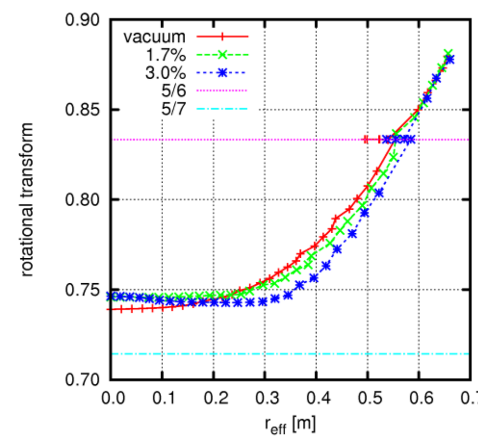
- **3D magnetic topology in stellarattor and tokamak is discussed.**
- **To model 3D magnetic topology, 3D equilibrium is very important. Numerical codes to calculate 3D MHD equilibrium**
- **Recent progress of modeling 3D magnetic topology are discussed.**
- **For V&V, systematic comparisons of experiments and simulations are very important.**

# Global effects or Local effects?

vacuum    Med.-density (β~1.9%)    High-density (β~3.3%)




•Clear flux surfaces are kept with increasing β.
•5/6 islands shrink due to increasing β.
•For β~2%, islands are almost healed.
•For β>3%, the phase of 5/6 islands changes.




Islands are healed without resonant current on 5/6 rational surface.

Contributions of non-resonant components.